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1984 IMAGE III CONFERENCE PROCEEDINGS

Compiled by

Eric G. Monroe

OPERATIONS TRAINING DIVISION
Williams Air Force Base, Arizona 85224-5000

September 1984
Final Report

LABORATORY

AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS 78235-5000

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The Public Affairs Office has reviewed this report, and it is releasable to the National Technical Information Service, where it will be available to the general public, including foreign nationals.

This report has been reviewed and is approved for publication.

MILTON E. WOOD, Technical Director
Operations Training Division

ANTHONY F. BRONZO, JR., Colonel, USAF
Commander

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These proceedings are a collection of papers presented at the 1984 IMAGE III Conference. The IMAGE Conference is devoted to issues relevant to the development and use of imagery generated and displayed for visual flight simulation. The purpose of the conference is to provide a forum for presenting and discussing topics concerned with the imagery generated for out-of-the-cockpit and sensor visual flight simulation. The conference was attended by more than 290 representatives of industry, military, aerospace, government, and educational institutions from the United States, Great Britain, Germany, France, Italy and Canada. The 31 papers were compatible with the theme of the conference, including both engineering and behavioral research and development (R&D). In the engineering area, papers covered such topics as visual data base development and management, automated and interactive data base development, digital radar landmass simulation, videodisc technology, light valve projectors, lasers in wide-angle displays, variable acuity displays, area-of-interest (AOI) displays, eye- and head-slaved AOI displays, fiber optic helmet-mounted displays, and reports on various existing and planned simulation systems. Topics in behavioral R&D included such items as effects of visual and motion cues, identification of targets in computer image generated displays, psychophysical aspects of visual processing, visual illusions, determination of visual cue requirements, transformation realism, and strategies to optimize CIG image content.

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flight simulation
helmet-mounted displays
helmet-mounted projectors
image generation
laser
light valve projectors
optics
projectors
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visual illusions
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1984 IMAGE III

MILITARY

AEROSPACE

GOVERNMENT

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The 1984 IMAGE CONFERENCE III

May 30 — June 1, 1984

The Pointe Resort

Phoenix, Arizona

Sponsored by:

The

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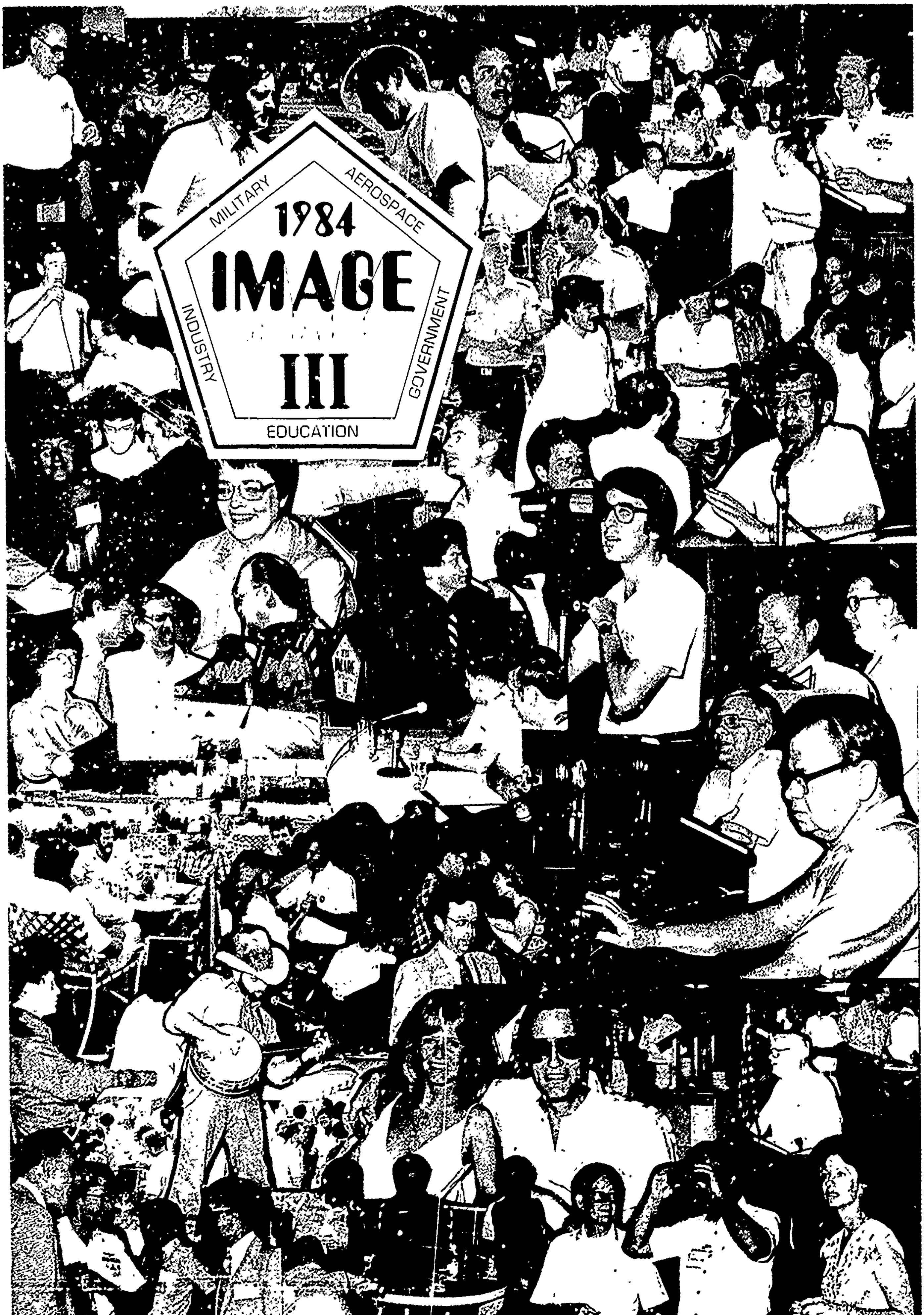
1984
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FOREWARD

The IMAGE Conference is the only major conference devoted entirely to issues relevant to the development and use of imagery generated and displayed for visual flight simulation. The purpose of the conference is to provide a forum for presenting and discussing topics concerned with the imagery generated for out of the cockpit and sensor visual flight simulation. The Air Force recognizes that the rapid technological advances and uses of real-time visual simulators requires that the interchange of information among the user organizations be expanded in order to promote new developments, applications, and techniques, and to avoid unnecessary duplication of efforts.

Papers are solicited in all areas compatible with the theme of the conference including engineering research and development, behavioral research, application and techniques, program progress and status, as well as technical problems and potential solutions. Pertinent topics include but are not necessarily limited to:

1. Software/hardware developments directly resulting in an enhancement of image capabilities.

2. Psychological determination of visual cue requirements.

3. Environmental data base design and structure.

The concept of the IMAGE Conference was conceived by Mr. Eric Monroe at the Operations Training Division (then the Flying Training Division) of the Air Force Human Resources Laboratory, Williams AFB, Arizona, in July 1976. The first conference was held at Williams AFB, Arizona, in May 1977, and was attended by 177 people. Attendance grew to 223 at the second conference held at the Registry Resort in Scottsdale, Arizona. Since its inception, the conference has been sponsored by this laboratory in a continuing effort to pioneer new methods and devices for aircrew training.

Eric G. Monroe

ERIC G. MONROE
Editor

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TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

TABLE OF CONTENTS
(Continued)

Visual Flight Simulation Considerations

INTRODUCTION TO THE 1984 IMAGE III CONFERENCE

It is indeed a personal pleasure to welcome you to the third IMAGE Conference. This year, 31 papers will be presented, and upon examination of the Proceedings I believe you will find the quality of the papers and expertise of their authors second to none in their field. In addition to the papers, a panel discussion entitled, "User Considerations - Where's the Beef?", has been established in order to encourage more audience participation. As you observe your fellow conferees, I believe you will find them to be neither lacking in experience or credentials. In attendance this year are international representatives of industry, military, aerospace, governmental and educational institutions.

The result of bringing together this broad spectrum of intellectual talents focusing on the central theme of visual flight simulation should have a synergistic effect in achieving our goals. The primary objective of the conference is to provide a forum for the exchange of information concerning engineering technology developments and behavioral research issues relative to effective and efficient pilot training with visual flight simulators. The objective of the conference has not changed over the last seven years, but many of the issues and technological capabilities have. Some of these will be raised in the papers and panel discussion over the next few days. Others will hopefully arise out of your personal interactions.

I believe you will find the environment at the beautiful Pointe Resort here in Phoenix, Arizona, provides an atmosphere conducive to stimulating thought and communication. May you find your attendance here most pleasant and productive.

ERIC G. MONROE
Founder and Chairman
The IMAGE Conference

Mr. Monroe, the Founder and Chairman of the IMAGE Confeience, holds the B.A., M.A. and M.S. degrees in mathematics from Washington and Jefferson College, Duquesne University, and Stetson University respectively, and an MBA degree from Arizona State University. He is a graduate of the Air War College, and member of the Phi Beta Kappa National Honor Society, and the Beta Gamma and Sigma Iota Epsilon National Management Honorary Societies.

Prior to joining the Operations Training Division of AFHRL, Mr. Monroe held positions with Duquesne University, the U.S. Army Chemical Corps, and the General Electric Company.

Having over fourteen years of industry and government experience in the field of simulation, he has held positions as systems engineer, project engineer, contract and program manager for numerous visual simulation applications.

COLONEL CARL D. ELIASON
Chief, Operations Training Division
Air Force Human Resources Laboratory
Williams Air Force Base, Arizona

Colonel Carl D. Eliason is Chief, Operations Training Division, Air Force Human Resources Laboratory, Williams AFB, Az.

Colonel Eliason was born January 4, 1938 in Kalamath Falls, Oregon. He graduated from Onida High School, Onida, South Dakota in 1956. He attended the South Dakota School of Mines and Technology and Brigham Young University receiving a Bachelors of Science degree in Industrial Psychology in 1960. He received the Master of Science degree in Systems Management from the University of Southern California in 1971.

Colonel Eliason was commissioned through the Officers Training School program in 1961. Following Navigation and Radar Intercept Training, he served in an F-101B Air Defense Interceptor Squadron until 1965.

Selected to attend pilot training, Colonel Eliason had subsequent duty as an F-105 pilot with assignments in the U.S. and the Orient. He is a Command Pilot and flew 145 combat missions from Takhli RTAFB, Thailand.

From 1971 to 1976 he served as Director of Test and Program Manager for Visually Coupled Systems at Wright Patterson AFB, Oh. He also performed duties as Chief of the Technology Development Branch of the Aerospace Medical Research Laboratory.

During 1976-78 Colonel Eliason was stationed at the Naval Air Test Center, Patuxent River NAS, MD as the Director of a joint USAF-USN Display Research and Cockpit Design Team. He spent the next 2 1/2 years in England as the Senior USAF Advisor to the Royal Air Force College at Cranwell.

From 1980 to mid 82 he directed the AFTEC SEEK TALK and JTIDS Test Teams at Eglin AFB, Fl.

COMMANDER'S COMMENTS

COLONEL ALFRED A BOYD, JR
Commander, Air Force Human Resources Laboratory
Brooks Air Force Base, Texas

Colonel Alfred A Boyd, Jr. is Commander, Air Force Human Resources Laboratory, Aerospace Medical Division, Air Force Systems Command, Brooks Air Force Base, Texas. He graduated from the Air Force Academy in 1963 with a bachelor of science degree and received a master of science degree in aerospace mechanical engineering from the AFIT in 1972. He is a graduate of the Air Command and Staff College and the Industrial College of the Armed Forces.

Colonel Boyd was commissioned upon graduation from the Air Force Academy and earned his pilot wings in 1964. After a tour as a F-101B Interceptor pilot at Griffis AFB, N.Y., he was transferred in 1967 to Southeast Asia where he flew over 300 combat missions in F-100F, O-1E, and 0-2A aircraft. Returning to the United States in 1968, Colonel Boyd flew F-101B and T-33 aircraft until his selection for AFIT in 1970. From 1972 to 1973, he served as reliability/quality assurance manager for the NATO phase III communications satellite program at the Space and Missile System Organization at Los Angeles Air Force Station, California.

After graduating from Air Command and Staff College in 1974, Col Boyd was assigned as Director of Operations and Training for the 56th Special Operations Wing, Nakhon Phanom Royal Thai AFB, Thailand. While assigned to the wing he flew OV-10A aircraft as a forward air controller. Returning to the United States in 1975, he was a T-38 instructor pilot at Craig AFB. While at Craig, he held several other positions including squadron operations officer and squadron commander.

Following graduation from the Industrial College of the Armed Forces in 1978, he was Director of Operations and Training, 20th North American Air Defense Command Region, Fort Lee AFS, VA. In 1980, he became the Director of Flight Support and Training, Detachment 2, Space Division, Manned Space Flight Support Group at the Lyndon B. Johnson Space Center, Houston, Texas. Colonel Boyd managed training programs for Air Force personnel during the first two flights of the space shuttle Columbia. In January 1982, he moved to Air Force Systems Command headquarters as Director of Electronics and Space Technology. A year later, he became the Assistant Director of Laboratories at the headquarters. He assumed his present position in April 1983. Colonel Boyd is a command pilot with more than 3000 flying hours. His military decorations include the Silver Star with two oak leaf clusters, Distinguished Flying Cross with one oak leaf cluster and nineteen air medals.

SESSION I

Low Altitude Flight Requirements

COLONEL MATTHEW R. KAMBROD, Session Chairman
Deputy for Aviation
Office/Assistant Secretary of the Army
Headquarters, Department of the Army
Washington, D.C.

Colonel Kambrod was born in December 1939, received a Bachelor of Science Degree in Engineering from the U.S. Military Academy, West Point, in 1962. He also attended the College of Naval Command and Staff and received his MS degree in International Affairs from George Washington University in 1973. In 1980 he graduated from the U.S. Army War College.

From 1973 to 1977, he was Aviation Staff Officer with HQDA Army Flight Standardization. Subsequently, he served as Commander, 7th Combat Aviation Battalion, Fort Ord, CA. From 1980-1981, he was War Plans Staff Officer at Headquarters, U. S. European Command.

Since 1981 he has served in his present capacity of Deputy for Aviation to Assistant Secretary of the Army (RDA). He is responsible for all matters pertaining to Aviation Research and Development programs. These include all current and future aircraft systems developed and procured to assist ground commanders in sustaining the land battle. He is also responsible for coordination of RDT&E matters in his functional area with OSD, the other military departments and agencies and activities outside the Department of Defense.

USING A LIMITED FIELD OF VIEW SIMULATOR TO INSTRUCT HIGH SPEED, LOW ALTITUDE FLYING SKILLS

by

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Captain Miller is a Fighter Weapons School Instructor Pilot with the 162TFG, Arizona Air National Guard. He has over 1800 hours of fighter time and over 1000 hours of Instructor Pilot time in the A-7D. He has spent the last three years developing a comprehensive low altitude training program which has received the full endorsement of the Air Force Tactical Air Command, the Air National Guard, the Canadian Air Forces, and all the major command Deputy Commanders of Operations. During the last 18 months Captain Miller has briefed over 1500 aircrews, 10 headquarter staffs, 50 general officers, written four safety articles, designed two low altitude training syllabi, and written a 250 page training manual. He has just completed writing, producing and narrating a 30 minute video tape on low altitude flying for world-wide Air Force distribution. He is currently writing the second edition of his training manual and preparing for a second video tape on visual illusions. Captain Miller is a 1973 Distinguished Graduate of the United States Air Force Academy with a B.S. in Engineering Management and an MBA from UCLA. He has received numerous awards for both his flying and academic skills and is recognized as a leading expert in low altitude training and visual perception, participating on several Safety Investigation Boards. He routinely interacts with AFHRL at Williams AFB, AZ and is currently involved with a project to collect physiological data during low altitude flights.

USING A LIMITED FIELD OF VIEW SIMULATOR
TO INSTRUCT HIGH SPEED, LOW ALTITUDE FLYING SKILLS

ABSTRACT

This paper describes the use of an A-7 Vital IV (three screen) visual simulator in a low altitude training program. This program is the first to use such a simulator in the training of tactical fighter pilots to operate in the low altitude environment. The program is part of the syllabus used in the Air National Guard, Fighter Weapons School program for highly experience A-7D pilots. The Low Altitude Training portion of this syllabus consists of 12 hours of academic instruction, a one hour simulator and a two phase flying program of at least two aircraft sorties. This paper discusses the simulator profile, explains each task, how it is accomplished and provides a subjective evaluation of its effectiveness. The paper identifies the training limitations imposed by such a low fidelity visual system, recommends several additional uses within the existing capability of the simulator, and identifies several minimum criteria for any "full mission simulator".

TRAINING PROGRAM OVERVIEW

The Low Altitude Training (LAT) program used in the A-7 Fighter Weapons School at the 162TFC, Tucson, AZ is a test program designed to make the pilots safer at their current level of tactical capability. The program has NOT yet been constructed within the guidelines of Instructional Systems Development or completely validated. However because it represents such a significant departure from the traditional ways of instructing LAT skills, it requires broad exposure and critical review. The use of the simulator is one of the most significant departures from the traditional "operational" use of this training tool and deserves special consideration. The LAT program, of which the simulator is a part, concentrates on four major areas related to the instruction of low altitude skills. The areas are:

a. Aerodynamics and physics,
b. Visual perception,
c. Cognitive capability; and,
d. Basic and tactical aircraft maneuvering.

The course involves 12 hours of academics, a one hour simulator and a two phase flying program involving basic and tactical maneuvering. Although the simulator appears to be a relatively minor part of the syllabus in terms of time, it represents a significant part of the learning. Its importance is confirmed by the course critiques which are very specific in identifying the value of the simulator in validating the academics and

building confidence before the flights. This is a rather surprising result given the typical fighter pilot response to the simulator which is usually neutral at best and most of the time, negative. The importance of this positive feedback can not be overstated. Low altitude flying has traditionally been thought of as the phase of flight MOST REMOVED from instrument flight and requiring the most "seat of the pants" skills for success. Because the operational application of this type simulator has been limited to instrument instruction only, it is indeed significant to have this use of the simulator score high with pilots. To show how this training effect occurs, each task of the simulator profile will be explained and a subjective evaluation of its effectiveness made. The following eleven tasks are accomplished by each pilot during his simulator sortie:

1. Head-Up-Display (HUD) and Radar Altimeter Cross-check
2. Angle Rate Tracking (fam)
3. Aircraft Stability (fam)
4. Dynamic Cockpit Tasking
5. Vertical Snakes (fam)
6. Speed Change (fam)
7. Vertical Jinks
8. Misperformed Jink (fam)
9. Level Turns
10. Masking and Rolling Terrain (fam)
11. Visual Flow Demonstration (fam)

The simulator sortie is supervised by an Instructor Pilot in a group setting so that each pilot can observe several others accomplishing the maneuvers, and practice each during his own turn in the "box". This approach accelerates the learning for all pilots because each task is reenforced at least 3 to 4 times by watching the repeater screens and listening to the Instructor comments. Seven of the maneuvers are accomplished for familiarization only (indicated by "fam" in the above list), and do not require any specific level of competency. The others, including five versions of the vertical jink, are graded items and have specific performance criteria based on the phyical sensitivity of the maneuver.

There are three scenes used during the simulator sortie. The primary scene is a 35 mile by 500 foot wide runway with edge and random center line lights. Although limited in texture and detail, it provides a highly predictable perspective cue. The slope of the runway is perfectly level because the simulator can not provide any slope that matches the radar altimeter. The area around the runway is totally black, like the night ocean with no lights. This area offers an exceptional opportunity to "set-up" some classic visual problems for the pilots. The second scene, used for the Masking and Rolling Terrain demonstration, is a series of alternating black and white, one mile by 1500 foot sloping squares which form a large washboard. The third scene, used for demonstrating and displaying what is meant by optical flow, is a cube of 16,000 light points. The use of each scene will be explained as the maneuvers are detailed.

The simulator cockpit matches the A-7 cockpit very well and all switches, instruments, displays and controls are available and working. It is in most pilot's terms, "a good simulator". The instructor console is capable and duplicates all instruments while showing the status of all switches and controls. It is easy to set up aircraft position parameters, visibility conditions and equipment failures to establish the desired effect.

SPECIFIC MANEUVER DESCRIPTIONS

1. **Head-Up-Display (HUD) and Radar Altimeter Cross-check:** This is the first task and has three specific objectives. The first objective is to allow the pilot to become familiar with the scene and the controls of the simulator. The second objective is designed to show the pilot some of the limitations of his visual perception, the conditions which can lead to ground impact, and how to use his instruments to prevent impact. The third objective is to insure that the pilot is proficient in the combined use of the HUD and radar altimeter by observing his altitude and vector control for various dive recoveries. The runway scene on the black background is used for these tasks and works very well.

Pilots quickly learn that distance judgement and altitude estimation are impossible over the black ocean, even with the runway fully visible across the front of the field of view. They learn that without the aid of a radar altimeter, impact is highly probable inspite of "feeling comfortable" because the runway is "just ahead". They learn that the eye cannot detect significant altitude changes, if the only cues are at long range where there is no discernable change in position, shape or movement associated with a change in altitude. This simple situation begins the process of developing a disciplined HUD and radar altimeter cross-check. It also begins the process of developing a real-time flight environment assessment skill. The flight environment assessment skills are designed to force a conscious decision about the quality of the flight environment which will then intercede over the subconscious cues and alert the pilot to dangerous conditions when everything, "feels OK". This exposure emphasizes the need for these skills which are outlined in academics and provides the pilot an opportunity to safely practice them. Although admittedly a degraded flight environment, this simulator scene compares well in terms of altitude insensitivity with several situations routinely encountered by pilots. Similiar problems are found over the water, snow, dry lake beds and just at dawn or dusk over the barren desert. This simulation is a safe and effective way of showing the pilot what can happen if he lacks conscious awareness of his visual limitations and what type of instrumentation he needs to operate in such conditions.

This straight and level flight through the dark, low density environment leads to the remainder of the HUD and radar altimeter cross-check evaluation. The second part involves a 2 to 3 degree, wings level dive at the runway. This is much like a landing approach. The pilot is shown the

perceptual effects which lead to the classic duck-under and short landing problem associated with weather approaches. He is placed 200 feet above the runway in a 2 to 3 degree dive with no instrumentation. With the simulator position frozen, the visibility is reduced, bringing the effective horizon in from 35 miles to 1/4 mile. A perceptual effect of increasing line of sight to the touchdown point is produced as the visibility is reduced. This effect is caused by the visible horizon intersecting a lower and lower position on the aircraft canopy structure as the visibility is reduced. This lower position is precisely what is seen when the aircraft is too high on final. If the pilot were to respond to these "normal" cues to a steep final, he would pushover to get the visible horizon back up to a higher position on the windscreen structure in an attempt to get back on his planned glideslope and actually duck-under and impact short. This demonstration closely duplicates the real world effects and again reenforces the need for both a cognitive awareness of visual limitations and a set of skills to counter its negative effects. This static exercise is followed by a series of dive recoveries based on specific HUD cues and radar altimeter values insuring that the pilot has developed an acceptable HUD and radar altimeter cross-check before proceeding with the rest of the simulator.

2. **Angle Rate Tracking (fam):** This familiarization exercise is accomplished over the runway to demonstrate the mathematical relationship between altitude and optical flow. The objective is to teach the pilot to look at, and track, specific objects traveling under and around the aircraft. It is an attempt to teach the pilot to use his central vision to judge altitude based on the angular rate of movement of the object he his tracking. The pilot flies at a specific altitude and velocity, usually 100 feet and 480 knots. He then picks a reference in the HUD and times how long it takes one of the runway lights to move from the HUD reference point and pass out of view. He does the same thing at 200 feet and determines that doubling the altitude doubles the time. He is then instructed to randomly change altitude, and using the timing references, estimate his altitude.

Although the simulation offers ample cues for accomplishing this task, there is a high rate of variance between pilots. It is an attractive technique because it involves a conscious estimation of altitude to supplement and possibly override the subconscious cues; unfortunately, its theoretical advantages are not consistently demonstrated in this situation. This exercise does teach pilots to look at and track objects around the aircraft. For many pilots this is the first time they have tried to do this at the lower altitudes. Although not yet specifically proven, it is my opinion that the pilot who tracks various objects around his aircraft will have better altitude and vector control in all flight environments. Further, he will be capable of safely operating in degraded environments where other pilots without these skills would fail. It would be very helpful if a research effort could validate the effectiveness of this technique for controlling altitude.

3. **Aircraft Stability (fam):** This is also a familiarization exercise but a very important element of the whole training program. The pilot's

knowledge of the aircraft stability and the time to impact produced by typical deviations forms the core of his task mangement in the cockpit. If this time reference is in error, he is either courting disaster or is tactically deficient. This series of maneuvers is designed to reenforce the time to impact calculations accomlished in academics. The maneuvers are flown over the runway at selected altitudes of 50, 100 and 300 feet with a dive of one degree and a ground speed of 480 knots. The pilot then simply flies the simulator into the ground noting the time to impact and the central and peripheral visual cues. He then is allowed to "practice" until he is absolutely satisfied that the physics are valid inspite of any previous perceptions of how much time was available. In all cases this is the first time the pilots have approached the ground at these rates of speed below 50 to 100 feet, and they typically spend a long time studying the sensations and visual cues offered by the simulator.

Although highly valuable, there are three significant limitations of this simulation. The first is the reduced density of objects available for producing optical flow. By comparing actual aircraft video of 50 foot dashes over the desert to the simulator scene over the runway, the difference in cues is dramatic. The next limitation, also related to hardware capability, is the pure level slope of the runway, a condition not routinely found in actual overland environments. The last limitation invloves the uncertainty about vertical obstructions like cactus, trees and wires. Again in actual 50 foot flight, there is an overwhelming visual workload associated with detecting the low contrast objects that are level or slightly above the aircraft. The limitations of the Vital IV system prevent the simulation of this task. Inspite of the somewhat benign environment of this stability exercise, it is successful in establishing the parameters for the entire cognitive process which the pilot uses to control all his low altitude tasking. It is the first half of a two part equation which insures that the right cockpit task is accomplished at the correct point. The second part is how long it takes to successfully complete typical cockpit tasks.

4. **Dynamic Cockpit Tasking:** This task has two parts. The first involves the timing of typical cockpit tasks such as switch changes, computer entries and instrument readings. The actual timing is accomplished by instructing the pilot to call out his start and stop times for a particular task such as a radio channel change and recording the results at the console. This activity provides the pilot with an objective, cognitive reference of how long a particular task requires for successful completion. These times are then compared to the impact times established in the aircraft stability exercise and conclusions drawn about where and when a particular cockpit task can be accomplished. This exercise is very effective in providing a "time map" of the cockpit for each pilot. If this is combined with specific maneuvers, then the pilot can logically determine a mental strategy for managing his tasks by matching tasking to maneuvers. For example, if he requires 13 seconds to accomplish a computer entry, he learns that it requires a level, 300 foot maneuver to safely complete it in an uninterrupted fashion. He could decide to accomplish the same task in two 7 second sections at 200 feet. Regardless of how long a particular task takes, the pilot can logically

select a safe method of accomplishment based on what was learned in these two exercises.

It is interesting to note that there is NO REQUIREMENT for a high fidelity mission simulator to accomplish this critical exercise. Skills such as "checking six" are easily accomplished by requiring the pilot to look over his shoulder at the Instructor Pilot sitting at the console and state the number of fingers he is showing. A trivial skill, but one that requires the same TIME as the airborne skill of looking over the shoulder and checking a wingman's six. This is a very powerful method of teaching time control because it is generic. It doesn't matter what the specific task is, only how much time it requires. Taking it one step further, each maneuver can be viewed as possessing a certain amount of free time that can be used for what ever task the pilot requires. If these times are learned, then the pilot can manage his tasks within the safe operating envelope with minimal effort by matching task to maneuver.

The second part of Dynamic Cockpit Tasking involves actual practice flying the simulator and accomplishing tasks. The instructor pilot instructs the pilot to fly at a certain altitude and directs him to accomplish certain tasks, some of which are impossible to safely complete at the given parameters. The pilot must correctly balance the maneuver and task time requirements to safely complete the task. The pilot's response to controlling his tasks is graded based on what combination of maneuver and task changes he makes to stay within the safe operating envelope. The difficulty and level of distractions are increased to thoroughly challenge the pilot's concentration and self-discipline. It is here that the pilot learns the selective attention skills and task management skills which will insure his surival in the low altitude environment. He practices until the Instructor Pilot determines that his mental discipline meets the expected standards for the flying phase.

5. **Vertical Snakes (fam):** This visual perception demonstration is designed to show the pilot the sensitivity of his peripheral vision to determine altitude and vector CHANGES. The pilot flies at 50 to 100 feet and begins a series of short duration up and down vertical maneuvers. He is told to note the rapid change in peripheral speed rush sensation and relate it to beginning altitude. He then doubles the altitude and notes that the same vertical maneuver produces a significantly lower level of speed rush CHANGE, indicating a HIGHER initial altitude. This effect is based on the changes in optical flow due to altitude changes and appears to be an effective cue for short term altitude changes. The runway environment offers adequate cues for instructing this effect; however, the visual effects may be more due to the change in perspective than the change in optical flow. It will require more experience over different environments to arrive at a firm conclusion. Questions of accuracy and validity associated with altitude estimation using this technique require more research and are closely related to the questions posed under the angle rate tracking exercise.

6. **Speed Change (fam):** This perception exercise is designed to show the effects of velocity changes on optical flow. It is accomplished at 50

feet over the runway and begins at 480 to 500 knots. The pilot stabilizes at that position for 15 to 30 seconds to condition both his peripheral vision and central vision to the optical flow. He then rapidly decelerates to less than 200 knots using idle power and speed brake, and notes the extreme changes in optical flow while holding the same altitude. Because he experiences difficulty in holding his altitude, this exercise accurately demonstrates to the pilot the perceptual inaccuracy of his visual system. The rapid slowing produces an overpowering tendency to LOWER the altitude as the speed slows. By freezing the radar altimeter during the deceleration, the pilot is usually completely unaware that he has lowered his altitude during the exercise. Although partially effective in the simulator, the relatively low density scene and the limited field of view compared to the aircraft flying over the desert, limits the impact. It is interesting to note that this speed change exercise is by far the most effective perceptual demonstration accomplished in the syllabus, an makes and intense impact on the pilots when accomplished in the aircraft.

7. **Vertical Jinks:** These five maneuvers represent aggressive tactical maneuvering and in most cases are taken to limits which are unfamiliar and well beyond the pilots' normal perceptual recovery point. For these reasons, they represent a powerful learning tool which combines memorized parameters with definite instrument cues to safely accomplish the maneuvers to a tolerance <u>not perceptually possible</u>. The maneuvers are repeated over the runway environment until proficiency and confidence are established. The pilots learn to control terrain clearance TOTALLY through the the control of vector geometry. No altitude instruments or perceptual cues are used; it is a single instrument maneuver. The pilots use the HUD to pull to a climb angle and then aggressively roll inverted, pull the nose of the aircraft down to a dive angle which is 10 degrees less than their climb angle, and recover. For example, if the pilot pulls to a 25 degree climb angle, he will learn to pull to only 15 degrees of dive and roll upright and recovery. This becomes the "10 degree", vertical maneuvering rule of thumb used for all vertical maneuvers. The techniques are repeated for both planned and random climb angles until they are accomplished correctly and without hesitation.

This series of maneuvers combines all aspects of the Low Altitude Training. The pilots must recall a set of rules based on aerodynamics, apply them through the use of an instrument and execute them accurately in the face of perceptual uncertainty. The benefits of establishing this cognitive process and the visual cross-check to support it in the safety of a simulator are critically important to the training program. It is during this exercise that the pilots develop the correct habit patterns and skills required for the flights. Without the simulator, a very gradual approach would be required during the flights necessitating more sorties. In many cases the level of tactical proficiency reached through the use of the simulator could never be obtained in the aircraft because of the uncertainty about the pilots capability and inability to catch any errors prior to impact. The runway scene adequately provides the necessary perceptual uncertainity involved in these steep, inverted maneuvers and supports the objective well.

8. **Misperformed Jink (fam):** This is a familiarization maneuver which demonstrates the limitations of the traditional vertical maneuvering safety rule of "5 degrees steeper than planned". In this demonstration the pilot pulls the aircraft to 15 degrees of climb and accomplishes a roll-in to 25 degrees of dive for a planned 20 degree weapons delivery pass. At the roll-out point in the dive, the aircraft is in an aerodynamically UNRECOVERABLE position. However, most pilots are perceptually comfortable with what they see and can not tell for the first 1 to 2 seconds that impact is imminent. This is another key lesson in visual perception for the pilot and emphasizes the importance of the cognitive rules established for the vertical jinks.

9. **Level Turn:** The high 'g', level turn is by most measures, the most difficult maneuver to accomplish in the low altitude environment. It is a difficult control task because of aerodynamic sensitivity and presents a very high risk of impact because of the low tolerances for error. A typical pilot deviation will cause an impact in 3 seconds from 100 feet, 5 seconds from 300 feet and 7 seconds from 500 feet. The typical safety buffer of increased altitude provides very little net increase when the time of error detection is considered. Because the typical control error causes an acceleration towards the ground, the point of no return is approximately one half the time to impact. If the error is not detected within the first 1.5 seconds from 100 feet, impact will occur. The pilot only gets a 1 second increase in this buffer if he increases altitude to 300 feet and another second by going to 500 feet. This insensitivity of safety buffer to altitude is not well understood by pilots and has contributed to inappropriate task management in turning situations. The reason for a severe misestimate of safety buffer is logical. In a wings level condition the typical control deviation provides 7 seconds to impact from 100 feet, 21 seconds from 300 feet and 35 seconds from 500 feet. This linear relationship of impact time to altitude leads the pilot to falsely assume that the same holds true for a turning situation. Worse, the majority of a pilot's low altitude flight time is spent in a wings level situation. This incorrectly leads to a false sense of safety based on altitude, because it is intuitively developed from the best possible case, straight and level.

The simulator is used to develop and evaluate the pilot's ability to accomplish the level turn within very tight criteria. Figure 1 is a page from the pilot's "Phase Manual" which explains how the maneuver is accomplished, the hints for successful accomplishment, the operating envelope which defines the maneuver, and the performance criteria for proficiency.

LEVEL TURN

EXECUTION:

1. Roll into the turn and apply "G" passing through 30° of bank and attain the desired "G" while adjusting bank angle to hold level flight.

2. By monitoring HUD FPM and canopy references, hold FPA between -1° and $+1^\circ$.

HINTS/COMMENTS:

1. Clear the turn prior to starting the turn.
2. Monitor the nose position relative to the horizon on a 1 to 1.5 second cross check keying on any small amount of lateral drop to the inside of the turn. Correct the drop IMMEDIATELY BY FIRST, decreasing bank; and second, increasing "G" (Typical TTI is 3 seconds at 100 AGL and 5 seconds at 300 AGL).
3. The HUD FPM is an excellent and the most consistent cue to FPA position and rate of change, and should be the primary point of reference in the during the LEVEL TURN.
4. If other tasks require attention, decrease bank; increase"G" and enter a climbing turn. DO NOT, REPEAT! DO NOT,TURN AND LOOK!
5. Be especially aware that the large build up of AOA (up to 10°) as the turn is started can lead to a FALSE perception that a climb has been initiated because the nose has moved up significantly relative to the horizon.
6. Anticipate a bleed off of airspeed and "G" available, thus forcing a decrease in bank angle to hold the LEVEL TURN.

OPERATING ENVELOPE:

1. $-1^\circ \leq \text{FPA} \leq +1$.

MINIMUM ALTITUDE PERFORMANCE CRITERIA:

From STRAIGHT AND LEVEL at 100 AGL, complete a 360° turn using a minimum of 4 Gs without gaining more than 100 feet at any point in the turn, or losing more than 25 feet.

Figure 1

The simulator offers is an excellent training aid for establishing the proper sequencing of the maneuver and demonstrating the various mistakes and corrective actions. The simulator allows the Instructor Pilot to evaluate the pilot's skills PRIOR to the first aircraft sortie where a 1.5 second mistake can lead to impact. For the first time it offers an objective and safe method of practicing a maneuver which carries such a high potential for error. This use of the simulator will allow training to open up tactical maneuvering windows previously unattainable because of safety considerations. With the simulator, forced performance can be safely accomplished which will lead to increased capability.

The current visual scenes do not adequately support this training. Several alternatives are currently being evaluated including a random spacing of lights over a surface. The density is planned for 15 lights per square mile which should be sufficient. The current scene requires too much reliance on the HUD for correct performance and not enough visual cues to show the desired effects of turning optical flow. The critical visual cue for aborting the maneuver, nose slice, can not be adequately demonstrated in the current scene and also requires more density.

10. **Masking and Rolling Terrain (fam):** This is a familiarization exercise used to establish the concept of using the changes in superposition or masking to detect very low contrast hills. The simulator scene is a series of black and white squares which slope up and down creating a large washboard. This is a marginally effective exercise because of the limited visual quality of the scene. The Vital IV has very limited capability for occulting and the desired effect is very difficult to see for most pilots. The pilot must rely totally on his visual perception to fly the contours because there is no land mass data correlated with the visual scene to provide correct radar altimeter altitude. Although limited in desired effect, the exercise again teaches the pilot that his visual peception is unreliable in certain types of flight environments and he quickly learns to pull-up and out of the hills to survive. The limited occulting capability significantly limits the training potential in this area. Future simulators must be capable of generating a visual scene correlated to a land mass so accurate instrument cues on both radar altimeters, forward looking radars, and other aircraft sensors can be integrated into a complete picture. Without this capability, pilots can not effectively use the simulator to learn the cross-check and task management skills necessary for safe, effective low altitude performance. This will be a minimum requirement for any "full mission" simulator.

11. **Visual Flow Demonstration (fam):** This demonstration is also accomplished in a special scene. The scene consists of a 16,000 light point cube suspended in space through which the pilot can fly. The purpose of the exercise is to teach the pilot the meaning of optical flow and how his vector and distance can be determined from just the angular movement of objects traveling through his field of view. Although it takes a fair amount of instruction, the pilots learn to precisely control their aircraft after a few minutes of flying the "star wars" scene. The objective is to dynamically demonstrate the techniques taught in academics. It is a successful exercise when limited to this purpose. Not to be forgotten is the entertainment value of this scene which by most critiques is rated very high.

This concludes the description of the simulator sortie. The sequence usually requires 45 minutes for the first pilot and about 30 minutes for each subsequent pilot. There is indeed a large amount of learning that takes place by simply watching from the console. There are some curious observations about the group interaction that takes place during the observation and simulator time. Competition is immediately established

with no prompting by the Instructor Pilot, and each pilot attempts to better the previous one. The acceptable performance parameters for each maneuver quickly become what the "best guy" did as opposed to what is written in the pilot Phase Manual. As an experienced Instructor Pilot, it is both surprising and rewarding to watch this amount of learning take place in such a short time, and all of it in an atmosphere of enthusiasm and competition. Although limited in its objectives, the simulator sortie is providing needed and quality training for the Low Altitude Training syllabus.

SUMMARY AND CONCLUSIONS

The routine use of the limited field of view simulator to instruct fighter pilots in the skills of high speed, low alttitude flight represents a new and creative use of a traditional training tool. The careful matching of learning objectives to the unique hardware capabilities of the existing simulator results in a product which is both acceptable to the pilots and highly efficient in teaching certain skills. The simulator sortie allows selected instruction to take place in all four areas of Low Altitude Training: aerodynamics and physics, visual perception, cognitive capability and basic maneuvering. The following is a list, in order of importance, of what the simulator successfully accomplishes in this program:

1. Verifys true aerodynamics and time to impact.

2. Establishes proficiency in applying cognitive rules for controlling aerodynamics.

3. Provides direct and objective feedback on time requirements for selected cockpit tasks.

4. Teaches specific cross-check and control skills for controlling maneuvers.

5. Demonstrates the fallibility of visual perception to adequately control aerodynamics in certain environments.

The only area not yet applied to the simulator is the tactical maneuvering. It is likely that a tactical training circuit can be built with the existing hardware, but it has not yet been attempted. With the addition of such a circuit, this simulator profile will allow the Instructor Pilot to objectively measure the integrated performance of the pilot as he balances the demands of terrain clearance against mission accomplishment.

Closing Remarks: It is obvious that a great deal of training effect is obtained with the existing hardware, but what about a true mission simulator? The first requirement is that the visual scene of what ever quality match a terrain data base for proper integration of aircraft sensors. The current LAT syllabus teaches the use of the Terrain Following Radar (TFR), but the simulator's quality is not even worthy of a familiarization event. The radar land mass does not produce reliable returns on the TFR scope, the radar altimeter does not match the terrain map and the visual scene is totally different and can not match the data base. This is a very serious limitation even for instructing day LAT where the radar altimeter is used as a verification for the visual cues. As additional sensors such as forward looking infared are added to the aircraft, this problem becomes even more accute.

The next serious limitation involves the visual scene. There is a basic and fundamental difference between the real world of flight and the simulator. The basic strategy of using visual cues is, in the vast majority of cases, opposite. In the real world, the key skill is selective discrimination, determining what to look at when. The environment is so rich with visual candidates that it can become overwhelming and a strategy must be deveoped to islolate the correct cues for flying the aircraft. Precious time can be wasted looking at a useless cue. The majority of cues available to the pilot are not usable but do compete for his attention both consciously and subconsciously. What about the simulator? Here the situation is just the opposite. Because of the severe hardware limitations, only a few objects can be displayed. The approach is usually to determine what the minimum requirement is for a specific task and go to that level and stop. Thus the pilot is not faced with a selection decision at all. His decision is to determine if the amount that is avialable is enough to do the job. He may often be forced to develop a way of accomplishing the task based on a combination of instruments and limited visual. This situation matches nicely the weather or night approaches, and produces a high degree of training effect for airline pilots and transports. However, when this basic approach is stretched to cover a day, tactical situation for a fighter pilot the system fails. The pilot actually creates a method of coping with the simulator scene, which may or may not have any transfer to the real environment. What can be done and is it really a problem? The choice may be to limit the uses of a simulator, but the answer is not currently available. There is very little data, if any, which says that selective discrimination is a required skill for simulator training. It may be so trivial that the existing simulations can teach the principals and let the remainder default to the aircraft. As aircraft instrumentation, controls and sensors become more capable and reliable, less and less pure visual interpretation will be required of the pilot. His skill requirements will switch more to the cognitive side and less to the perceptual side, making training ideally suited to the simulator.

Although it is difficult to determine exactly how much of a role simulators will play in the Low Altitude Training area of the future several key changes are driving the decision for more use. The first factor is simply airspace. The areas of the world over which a fighter

pilot can fly at 50 or 100 feet are extremely limited and getting smaller by the year. Without the area to train and practice, the burden of training and proficiency must fall on the simulator. The second factor which is forcing more use of the simulator is the increasing complexity of the cockpit workload at low altitude. With increased workload, the pilot must become more proficient at what he does in the cockpit. He must learn to throw more switches faster, and make decisions quicker if he is to dedicate the same amount of time to avoiding the ground. The simulator is ideally suited to this type of training because of its inherent safety and observation and feedback capabilities. The last factor is a pure resource consideration. As tactical aircraft rapidly approach the 50 million dollar per copy price range, it becomes apparent that the traditional low altitude loss rates are completely unacceptable. Commanders will demand that pilot error accidents be reduced to the lowest possible level commensurate with preserving capability. As shown by the creative application of a limited capability simulator such as the Vital IV, a great deal of training effect can be obtained from a relatively unsophisticalted piece of equipment, if it is properly used. With advances in hardware, **DRIVEN BY OPERATIONAL AND TRAINING REQUIREMENTS**, simulators could become a primary method of training for all phases of flight, even for the low altitude fighters.

VISUAL PERCEPTUAL ASPECTS OF LOW LEVEL HIGH SPEED FLIGHT AND FLIGHT SIMULATION

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CAPT MILT MILLER is a Fighter Weapons School Instructor Pilot with the 162TFG, Arizona Air National Guard. He has over 1800 hours of fighter time and over 1000 hours of Instructor Pilot time in the A-7D. He has spent the last three years developing a comprehensive low altitude training program which has received the full endorsement of Tactical Air Command, the Air National Guard, the Canadian Air Forces, and all major command Deputy Commanders for Operations. He has briefed over 1500 aircrews, 10 headquarters staffs, 50 general officers. He has written four safety articles, designed two syllabi, and written a 250 page training manual. He just completed writing, producing and narrating a 30 minute video tape on low altitude flying for world-wide Air Force distribution. He is currently writing the second edition of his manual and preparing for a second video tape on visual illusions.

Visual Perceptual Aspects of Low Level, High Speed Flight and Flight Simulation

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INTRODUCTION

The low level high speed flight arena has opened up as a very important one in the past several years. Weapon systems and tactics developments have forced the acquisition of pilot skills in low level, high speed flight. In order to remain undetected and complete his mission, the pilot is forced to fly below enemy radar. This carries with it the constant threat of contact with the ground, which is of course as lethal as enemy missiles. As a consequence of this necessity to fly low and fast, a thoroughgoing training program has been under development for the past three years at the 162nd Fighter Weapons School, USAFR, Tucson, Arizona, in collaboration with the

Human Resources Laboratory, Williams AFB, Arizon· Most of the substance of this paper is a direct result of this collaboration.

The aim of the Fighter Weapons School is to develop a comprehensive training program which will take pilots through a regorous academic and applied course which will optimally prepare them to perform in the low level, high speed environment. This program will include training development as well as ongoing research to answer the many questions which have emerged from this endeavor. Transfer of training and follow-up evaluation studies will clearly play an important role in this effort. The end result will be a holistic approach to the subject which will consider its many facets and complexities.

The purpose of the present paper is to describe in some detail the visual/perceptual aspects of low level, high speed flight as they are currently viewed by the developers of this program. The flight simulator has already begun to play an important role in this training program, and this role will certainly expand with the fast developing simulator technology in conjunction with better understanding of the training requirements.

THE PILOT AND VISUAL PERCEPTION

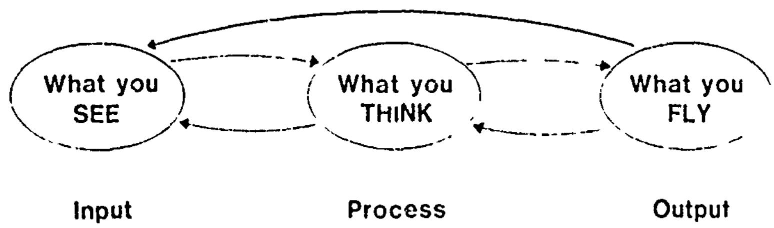
During a pilot's training program, very little time is spent on the subject of vision and visual perception. The material covered in Physiological Training is excellent, with respect to the basics of Night

Vision and Spatial Disorientation, but it is unfortunately not sufficient to deal with the complex visual problems involved in low level, high speed flight. The pilot will have to learn more about visual perception in order to fly safely in this environment. The general approach which has been taken to accomplish this is to cover the basic information available to visual scientists as it applies directly to flight operations. Of course, visual science does not have the answers to all the questions posed by this kind of flying, but many are available and ready for application.

WHY DO PILOTS HIT THE GROUND?

Visual perception or what is "seen" is a complex relationship between the eyes and the mind. There is a physiuological part associated with reflected light, response time, contrast, threshold, etc., and a psychological or cognitive part associated with interpretation of the physiological stimulus. Generally there is a constant cycle going on: the eye "sees", the mind interprets, "perceives" and a reaction is determined and executed which often changes what the eye "sees". Other times the eye is directed to gather specific information so that the mind can assess the progress or an ongoing action or decide when to start a specific action. This constant interplay between the visual environment, eye and mind is depicted in Figure 1.

WHY PILOTS HIT THE GROUND



REASONS	MUST TEACH
Incorrect Inputs → "What you see"	"HOW TO SEE"
Incorrect processing / Slow processing → "What you think"	"HOW TO THINK"
Incorrect output → "What you fly"	"HOW TO FLY"

Figure 1

Any one of the tracks can be used in low altitude flying. Sometimes the cognitive process uses the eyes for determining if the aircraft is in the right spot for an upcoming maneuver, and sometimes the brain simply reacts to a specific unrequested input from the eyes such as a non-moving spot on the windshield. It is important for all pilots to understand that they can die from three basic causes:

Incorrect Inputs	"What They See"
Incorrect processing or Slow Processing	"What they Think"
Incorrect Output	"What They Fly"

Visual perception is a key to all three causes. If the incorrect visual information is seen, it doesn't matter how great the decision process or execution procedures are, the result is still wrong. Likewise, if the correct things are seen, but processed or reacted to incorrectly or to slowly, then the results are likewise wrong. If the deviation in maneuver execution can't be seen, then the maneuver is uncontrolled, with expected results. Procedurally, the pilot is taught: (1) what to look for, (2) when to look for it, (3) how to use it, and (5) how to check its results.

VISUAL PERCEPTUAL CUES

Basically, to survive in low level, high speed flight, the pilot needs to understand thoroughly (1) where he is, (2) where is is going (complex reactor analysis), and (3) how long it will take to get there. Visual perception is of primary importance in getting and maintainint this information.

Within the brain, other bodily sensations, such as the vestibula senses of "G" and motion, and feedback from the physical control inputs are correlated with the visual ensations. The brain compares the results with remembered sensations from past experience, modifies them according to attitude and intent, and then produces in the conscious mind information about what is seen. This information constitutes the perception of objects and motion. The perception may be correct or incorrect, depending in part upon attitudes and experience. An illusion is a faulty perception caused by some unusual presentation of the scene or by some missinterpretation of the observer.

There are two basic types of visual cues used by pilots to control their low altitude operation: static and dynamic. The static cues are available without aircraft motion, but when combined in a time series show a great deal about motion. The dynamic cues are a direct result of the movement of the aircraft relative to everything in the pilot's field of view. The dynamic cues are much less well understood, but by their nature, become very dominant cues in high speed, low altitude flight.

STATIC VISUAL CUES

The static cues of importance to the pilots are (1) Linear Perspective, (2) Masking, (3) Elevation, (4) (Brightness, (5) Texture/Detail, (6) Known Size, and (7) Binocular. Each of these must be understood and incorporated into the pilot's awareness during low level, high speed flight.

Linear perspective is the representation of distance change such as seen in a railroad track converging in the distance. It is a frequently used cue by the pilot for judging distance. Distant objects form smaller images on the retina than do nearby objects. The problem is to determine whether a particular object is small and close by, or large and far away. The value of linear perspective is high even in unstructured flight environments, becuause it represents the physical fact that objects of equal size get smaller at a linear rate with distance from the pilot. Linear perspective offers a method of scaling distant objects based on the size of near objects. Any change in linear perspective means a change in size. Pilots must learn to detect the

true size of objects with distance to prevent false lowering of the above ground level (AGL) in an attempt "to keep the bushes the same size." It is assumed that by consciously looking for and using this effect to mentally note size changes, a pilot will increase his ability to correctly assess distance or AGL in the absence of other cues. Time and pilot feedback will tell if this assumption is valid.

Masking occurs when one object overlaps another and partially obscures it, with the result that it appears to be nearer. The amount of masking is very obvious in low altitude flight as near objects mask those at a distance. Further, as altitude gets lower, the point of unmask gets closer and closer to the aircraft, producing a good realtive cue to AGL. The problem is that masking depends on the relative size of the objects as well as their position. Large, near objects obviously mask more objects for a longer period of time than smaller objects. Still, it is a very useful cue, expecially when observed over a short time at low altitudes. The "unfolding" or unmasking rate varies with both AGL and speed to give the pilot a good cue to changes in these variables. This effect is obvious in flight over desert areas covered with small bushes. Thus, masking not only gives information on the relative distance of objects, but also gives a good cue to AGL.

Elevation considerations also give good cues to spatial orientation. In a picture of a landscape, the horizon is always higher than the foreground. Objects that are higher or further from the bottom of the picture always appear to be a greater distance aweay. Although a good cue for relative positioning, the dynamics of low altitude maneuvering in the looking down

viewpoint makes it much less usable than masking for specifically controlling AGL or vector. The one exception to this involves flight in low ceilings or poor visibility where the perceived horizon is moved closer to the pilot or lower in elevation due to the intersection of the clouds and the ground short of the real horizon. In these cases, it is very likely that the pilot will lower his AGL in an attemtp to "visually raise" the perceived horizon up to its normal elevantion relative to his sight line. This natural reaction to a misplaced elevation cue accounts for the common tendency of pilots to "duck under" or drop below the glide slope when they break out on a weather approach. The same effect can occur when similar conditions are encountered along a low level route.

Brightness can also provide a cue to depth or distance. Bright objects are perceived as being closer than dim objects. This effect is also of limited utility in low altitude operations and is usually dominated by other cues. It does, however, explain why city and other lights appear much closer at night and why a wingman appears to change distance when he goes into or out of a shadow. It is more an observable effect than one that has a specific use in controlling AGL or vector. It can lead to confusion when visually searching for small hills along the flight path under a scattered cloud deck. The changing brightness can confuse the distance estimation established by other cues such as masking, creating a momentary visual ambiguity which must be resolved by dedicating more effort to terrain clearance tasking (TCT).

Texture/Detail can also be a factor in depth perception. Sharp edges and clear details imply closeness. Haze and fog enhance the appearance of depth.

They make distant objects less distinct than those nearby, and some not-so-distant objects become blurred. This tends to compress the scale of distance. More obvious is the lack of detail on objects at a distance. Because of linear perspective, as the distance gets larger the amount of observable detail becomes less and less providing a very good cue to realitve distance. Objects of equal surface texture and detail are then judged to be equally distant, if other cues are absent. This cue is very helpful in AGL control. A conscious observation of the detail or texture available on a specific object gives an immediate scaling of distance. Although it is possible to misperceive the size of the desert bushes, if the limbs are easily visible with sharp, crips shadows, then it must be close, regardless of other available cues. Texture/Detail is best used to validate a known size perception.

Known size is one of the most important cues to distance. It is simply, the judgment of size of an object, and consequently its distance away, based upon cognitive knowledge of the object. A Ford pickup truck always appears to be cognitively the same size, no matter how far away it is viewed. Since the further away it is viewed, the smaller will be the visual angle, a determination of its distance away can be made. The object, of course, must be identified correctly and if it is misidentified, such as assigning desert bushes the size of familiar trees, a known size illusion occurs. It must be consciously controlled, especially in areas where there are few man-made objects of known size. The pilot must be particularly suspicious of his AGL perception in areas devoid of known size references. Combining known size with Texture/Detail is a good way to prevent the false size illusion. A small

bush will provide the same amount of detail as a large bush at the same distance. Therefore, regardless of the perceived or "feeling" of high AGL produced by knee-high desert bushes, if the branches and limbs are visible and detailed then they are close (low AGL) even if they are subconsciously perceived as big bushes viewed from a high AGL.

Binocular cues have been given a great deal of emphasis in pilot selection and flight physicals, but there is little evidence in support of the assumption that these cues are used in most flight tasks, including low level operations. The ability to tell distance solely on the angular difference between the two eyes does not extend beyond 25 to 50 feet with some slight evidence supporting distances up to 100 feet. More importantly, the cues become obscured at the high rates of object movement associated with AGLs equal to these distances. At low altitude and high speed, the binocular cues become virtually useless as a cue to distance. Their best contribution comes only from the fact that the field of view is expanded by about 50%, especially around aircraft structures such as canopy bows, thus providing more visual information at each instant of time.

DYNAMIC VISUAL CUES

Dynamic visual cues fall into two basic categories: (1) Motion in static cues, and (2) Flow patterns and angle rate of movement. These two areas will be take up in turn.

Motion in static cues, refers to motion perception produced by summing a series of static views over time to produce a cognitive picture of velocity and direction. This building of scenes or visual construction is a very powerful visual cue for the pilot. He must learn to key on changes in the direction displayed by the successive views of a scene to control his vector and cognitively determine his AGL.

Flow patterns and angle rate of movement refer to the dynamic and continuous movement of the visual field. This is, of course, the way the pilot sees the real world, in real time as he controls the aircraft. Flow patterns may be represented pictorially by views out of the cockpit which show vectors of movement as they unfold during maneuvers. Angle rate movement may be represented by three dimentional plots which show the angular movements of the aircraft as it goes through maneuvers. By use of such pictorial representations, the pilot is able to get a clearer understanding of the moment-to-moment changes which occur in real flight.

GLOBAL AND FIXATED FLOW

There are two fundamental modes of operation of the visual system which come into play in piloting an aircraft, as well as most other activities. They are (1) Global, and (2) Fixated vision. Both of these systems work in concert to produce the total visual perceptual awareness of the pilot. The global system encompasses all the retinal stimulation outside the fovea, while the fixated system is concerned with the information gathered and integrated

in the small visual angle of the fovea. In general, global vision is a subconscious perception, instinctively applied while fixated vision must be learned and consciously controlled [H. Leibowitz has described these systems very well. He has called them ambient (global) and focal (fixated)].

The global flow system uses the entire field of view of the eye and interprets the movement of all objects except the fixation point which is stationary, to arrive at a perceptio of distance, direction and velocity. Velocity induced blur patterns or streaking of light across the retina form flow patterns which become useful as a method for perceiving the angle rate of movement in physical space. That is, if the pilot were to fixate at infinity through the velocity vector, every object would produce these streaks precisely showing all angle rates of movement in the field of view. From their length and direction he could visually determine direction and velocity. With either physical distance or velocity known, he could then determine all three accurately; distance, direction and velocity.

This global method of seeing is very good at determining small, short term deviations in aircraft vector, but is susceptible to both conditioning and visual environment changes. In this regard it cannot determine if the altitude was 50 feet and is now 100 feet, only that a slowing of the flow patterns was detected. It is up to the pilot's conscious understanding of the visual effort to determine if altitude increased, flight path angle changed, speed decreased, or fewer objects are crossing the field of view. In other words, it is a very good cue for detecting short term changes, but because it is ambiguous and for the most part subconscious and automatic, other cues and knowledge must be applied to determine what is actually happening.

The fixated flow system is the second way the aircraft velocity vector can be seen by the pilot. The method requires conscious control and can work very well to remove the ambiguities from the global flow responses. This way of seeing requires the pilot to periodically look at, lock onto (fixate), and track a particular object in the visual field. This conscious angle rate tracking, when combined with an aircraft structural reference, matches precisely the physical angle rate of movement of that object. This technique can provide accurate and consciously controlled visual cues to distance, direction and velocity. This kind of tracking is an easy visual technique to learn and holds up very well in varying terrain and visual environments. It is even possible, using aircraft heads up display symbology, along with time, to accurately measure AGL. Because the pilot is measuring a true physical quantity by measuring the time it takes an object to travel a given angular distance, the resulting time in combination with a known ground speed and flight path angle produces a "measured" AGL result. The preferred method for obtaining fixated flow cues is to track specific objects through a given angle, usually referenced to either heads up display, manual pipper or aircraft structure. By practicing and relating the time it takes the object to move between the references, an accurate and reliable visual cue to direction, velocity and distance can be developed. Further, if this technique is practiced at normal maneuvering speeds, very precise AGL estimates can be made in spite of conflicting static cues such as a false size perception. After a little practice, visual AGL estimates become both precise and easy.

FLIGHT ENVIRONMENT ASSESSMENT

In order to effectively deal with the low level flight environment, it becomes necessary to quantify and evaluate the specific visual cue areas in which the pilot flies. Experienced pilots know that the type terrain, visibility, sun angle, ceiling, horizon and a host of other factors have a direct impact on the precision with which they can maneuver the aircraft and at what AGLs they can safely, visually accomplish their maneuvers. They also know that the flight environment can be a very uncontrolled quantity, changing rapidly with heading changes within seconds or minutes along a route. It is therefore necessary to develop a method of assessing the low level flight environments in both real time out the cockpit window, and prior to the flight from maps, photographs or previous experience. In short it is necessary for each pilot to learn how to predict the effectiveness of his visual system in all flight environments.

In order to evaluate the visual environment, a five part rating scale has been developed to more systematically access the visual scene. The five factors consists of: (1) Density, (2) Known Size, (3) Texture/Detail, (4) Terrain Gradient, and (5) Unacquired Verticle Obstruction. Each of these five factors is graded along a scale of 1 to 5 and then plotted on a graph which then quickly identifies the nature of the visual environment. Space does not permit a more detailed description of this method here, but is available in the full training syllabus.

SIMULATION OF LOW LEVEL HIGH SPEED FLIGHT

The flight simulator clearly has a large role to play in the training of pilots in low level high speed flight. In the past, flight simulators have not had the level of sophistication to deal with this complex environment. However, now with the development of elaborate visual systems, including texturing, high resolution, color and visual motion accuracy, the simulator is emerging as a valuable and cost effective tool in the training of pilots in this complex and difficult area.

ALTITUDE CONTROL USING ACTION-DEMANDING INTERACTIVE DISPLAYS: TOWARD AN ACTIVE PSYCHOPHYSICS

Rik Warren & Grant R. McMillan

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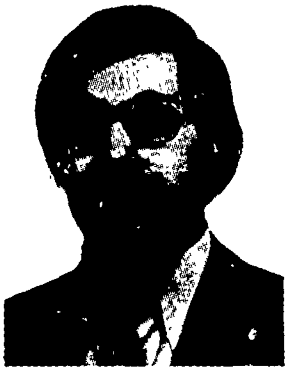

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ALTITUDE CONTROL USING ACTION-DEMANDING INTERACTIVE DISPLAYS: TOWARD AN ACTIVE PSYCHOPHYSICS

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Abstract

Ecological approaches to perception and action emphasize the importance of exploration and manipulation for obtaining useful information. This seems to apply to the demanding task of low altitude flight. However, the ecological approach currently uses the same passive methods used in traditional psychophysics: Observers may only respond to a display in a manner which does not affect the display (e.g., yes/no or scaling judgments). Observers generally cannot manipulate the display to provide information which they -- and not the experimenter -- determine. A new methodology which both permits and demands observer action is needed for active performance. This paper outlines the beginnings of an active psychophysics and illustrates the techniques with an experiment designed to evaluate altitude holding in the presence of a gust. Initially, the techniques borrow heavily from those in manual tracking studies. The displays are a joint function of experimenter chosen initial conditions, observer control inputs, and a continuous gust disturbance. Sum-of-sines forcing functions and human operator describing functions are highlighted.

Introduction

High-speed low-altitude flight requires precise altitude control using outside-the-cockpit visual information. There are three basic problems concerning altitude control information that need to be solved in order to understand such flight in general, and in particular, to design flight simulators for optimal pilot training and proficiency maintenance. The problems are:

1. Ascertaining that all critical information a pilot uses is in the simulated display.

2. Assessing pilot sensitivity to altitude control information.

3. Evaluating information usage, that is, developing performance metrics which are relevant to the pilot's task.

The paper first assesses current research into these problems, and concludes that not only is "further research indicated", but that a whole new methodology needs to be developed. The case for an "active psychophysics" is then presented in detail since it motivates the kind of displays we use in studying altitude control. These displays are both interactive and action-demanding and can be used in other areas of perceptual research. Lastly, we report an experiment on altitude control using these techniques.

Problem Assessment

The problem of ascertaining necessary information is important to designers of data bases. Since we do not now know just what the critical information is, current simulator designers must attempt to provide as realistic a scene as possible. Although this seems a reasonable, albeit expensive and wasteful approach, static scene realism may not in itself provide the critical information. Rather, the critical information may be provided by dynamic transformations of the scene produced by the observer's own motion. That is, the necessary carriers of altitude control information may not be the scene elements themselves, but rather what happens to the scene elements. If this is true, we may use convenient scene elements such as a random dots instead of something more complex, and we should concentrate on defining these scene transformations and ensuring their presence in simulators.

The problem of assessing sensitivity to altitude information is generally considered a detection and scaling problem. Researchers have investigated absolute judgments of altitude using static pictures (Rinalducci, DeMaio, Patterson, & Brooks, 1983) and sensitivity to changes of altitude using moving scenes (Owen, Warren, & Mangold, in press). Although the questions asked are straightforward and the findings important for a complete understanding of altitude control, it is not at all clear how to use the answers. Can we with confidence now tell pilots not to fly level below a certain altitude? How is a pilot or simulator designer to use a particular threshold or signal detection value?

The problem of information usage has either been ignored or equated with that of information detection. Although a threshold may be considered a performance metric of sorts, we are concerned with more direct and task relevant performance measures. One way of achieving such measures is to equate "information usage" with "control action". An example of this approach is Mitchel's (1982) study in which she used control performance directly to evaluate the effects of size and location of scene elements on altitude control. What follows is thus an attempt at understanding flying by more closely integrating perception with action for survival.

Ecological Reformulation of the Problem

High-speed low-altitude flight demands continuous and accurate perceptual and control activities. Further, the perceiving and controlling must be so closely coordinated that we may consider them as two aspects of a single survival-oriented process. By focusing on "perceiving-acting", rather than on "perceiving" and "acting" separately, we may gain an edge on solving the important coordination issue which otherwise is merely postponed or ignored. Indeed, ecologically-oriented theorists argue that such a unified approach is essential to understanding perception and action in real world situations (Gibson, 1979). Thus, we turned to this approach in our studies of the perception of egomotion and flight control.

The ecological approach to perception and action emphasizes the importance of exploration and manipulation for obtaining useful information. In developing his approach, Gibson (1966, ch. 2; 1979, ch. 14) distinguished between imposed and obtained stimulation. Imposed stimulation implies a

passive observer and is associated with traditional theory and research on perception. Such research utilizes the passive techniques of traditional psychophysics. Methods for obtaining thresholds, psychophysical scales, and signal detection indices are passive since observers may only respond to a display in a manner which does not affect the display, e.g., using yes/no, rating scale, or magnitude estimation judgments. Observers generally cannnot explore or manipulate the display to make available information which they -- and not the experimenter -- determine. Stimulation is imposed both because of the needs of a sensation (as opposed to an action) based theory of perception and because of presumed good scientific methodology: Traditional psychophysics purports to rigorously isolate both the "stimulus" (since only the experimenter affects the display) and the "response" (since the observer's repertoire is tightly constrained) and thus enable the drawing of lawful relationships between the two.

Well-intentioned as this is, the approach is open to charges of ecological non-validity in both the stimulation and activity permitted an observer. This makes the findings (e.g., thresholds, sensory scales) irrelevant for understanding (1) how animals pickup information to guide their actions, and (2) how they act to make information available (Gibson, 1979).

In light of the emphasis of ecological researchers on self-obtained stimulation by manipulatory and exploratory activity, it is odd that current ecologically-motivated research uses the same passive methods as traditional psychophysics, e.g., Owen, Warren, Jensen, Mangold, and Hettinger (1981). Passive techniques are still used primarily because an active psychophysics has yet to be developed.

Toward An Active Psychophysics

Active psychophysics both permits and demands action by an observer. The permitting of action means that an observer can affect the available display of information. The use of a dynamic display, such as in a flight simulator, does not in itself constitute active psychophysics if the observer cannot influence the display. The display must change, at least in part, due to the actions of the observer.

The demanding of action means that the observer <u>must</u>, in fact, <u>do</u> something which entails attending to the display and controlling some feature of it, or else suffer a (possibly simulated) consequence. In real life, animals not only have the option of seeking information and acting, but are forced to do so by the requirements of survival. Perception and action are generally motivated and purposive in an eat or be eaten world.

How is action to be demanded of an observer and how are the data to be analyzed? As a beginning, we borrow heavily from the methods developed for the study of compensatory tracking and manual control (Junker & Levison, 1980; Poulton, 1974). More generally, ecological psychologists can profit from control theory, dynamic systems analysis, and time series analysis (Gottman, 1981; Gregson, 1983; Toates, 1975).

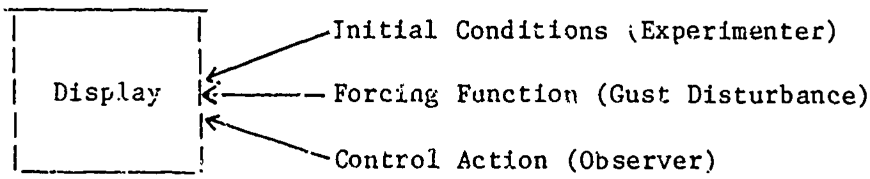
We emphasize that this wholesale importation of techniques is only intended as a beginning. The methods of differential equations and cross-correlations, however sophisticated, are not yet sufficient to enlighten us in

the processes involved in many mundane but ecologically vital scenarios. Active psychophysics can be characterized not only by a methodology but also by the problems it addresses and the displays (visual or non-visual) that it employs. Selection of problems and displays should be guided by the needs of perceptual theory and not by the availability or tractability of mathematical and computer graphics techniques. With these caveats and the hope that engineering elegance does not replace psychological insight, we turn to these techniques.

Overview

The approach essentially involves assigning an observer a difficult tracking task requiring skilled perceptual and control abilities. The observer acquires information and feedback to guide his action via a dynamic display which is jointly determined by the observer's own action and by a perturbing input. This perturbation forces the observer to continuously "work" to achieve his goal and holds the key to the data analysis. There are actually three determinants of the display (Figure 1):

Figure 1



Initial conditions. The initial state of the display is determined by the experimenter. It may be as rich or impoverished as the experimenter cares, and different parameters may be varied from trial to trial as needed by the investigation.

Observer action. The display is dynamically changed as a function of the observer's control action. Typically this involves a set of dynamics which relate changes in the observer's controls to changes in the display. The particular dynamics depend on the application and available resources, but the main consideration is real-time implementation with an appropriate sampling/update rate and a small lag occurring between the control action and its effect.

Forcing function. The display is continuously perturbed by a "forcing function". This pertubation may be linked to the observer's action or some system state. Linked forcing functions are used in making donkeys follow carrots or dog's chase their tails. A more humane forcing function is independent of the system states and may take the form of a random or quasi-random pertubation. The random sequence may be precomputed for a trial and affect the display through its own set of dynamics. In addition to making the observer work to achieve success, a properly chosen forcing function can be a powerful tool for analysis. We recommend using a quasi-random forcing function such as that described in Junker and Levison (1980): A random appearing series is formed by summing a carefully chosen set of sine waves so that its power

spectrum approximates that of a task-relevant real world perturbation.

Data. The data consist of several time series including: the forcing function, the observer's control inputs, the RMS tracking error, the display parameters, and other system states.

Data analysis. Since the forcing function was composed of a set of sine waves, the experiment may be viewed (assuming certain linearities) as a set of simple sine wave tracking experiments conducted simultaneously. We seek to know how well each separate sine wave was tracked. The first part of the data analysis thus consists of obtaining the power spectra and phase characteristics (using Fourier transforms) of the several time series. (The power spectrum of the forcing function should check with the intended spectrum.)

The second part of the analysis compares the power and phase of the "output" sine waves (e.g., the observer's control actions) with those of the "input" sine waves (the forcing function or the display). These comparisons, viewed as a function of frequency, are called "describing functions" and are obtained using the procedures in Junker and Levison. The "human operator's describing function" basically answers three questions regarding how well an observer tracked (that is, reproduced) the simple sine waves comprising the input: (1) How well are the amplitude and power of the target sinusoid reproduced? This is the gain question. (2) Is there an anticipation or lag in the tracking of a target's motion. This is the phase question. (3) Does the reproduction of the target sine wave include any power at other than the target frequency? That is, did the observer introduce any "alien" components into the reproduction? This is the remnant question. Examples of describing functions in an experiment using both visual and non-visual displays are given in McMillan, Levison, and Martin (1984).

Application to Altitude Control

Altitude holding in the presence of gusts epitomizes the continuous interplay of perceiving and acting. Since we do not now know which of the many cues to altitude are, in fact, used by pilots nor what their control stategies are, we are undertaking a program of cue evaluation using active psychophysics with a further aim of performance modeling. In the experiment reported here, we restricted the cues to those available from a simple roadway scene and the control actions to pitch adjustments only. However, within these domains, cue and control states changed continuously by dynamic interactions. The experiment closely followed the recommendations of Levison, Zacharias, and Sinacori (1982).

Method

Observers

Six people (three men, three women) participated. None were pilots.

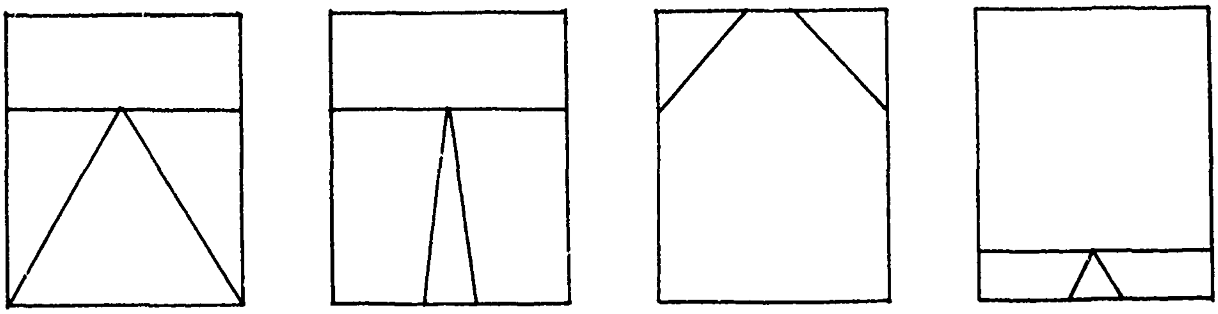
Displays

Basic appearance. The displays were computer generated scenes consisting of line drawings of a perspective view of a road and a horizon. The central

perspective angle of the road changed as a function of altitude, and the position of the horizon line changed as a function of the pitch state of a simulated aircraft. The left two frames of Figure 2 indicate level flight at low and high altitudes. The right two frames indicate pitch down and pitch up states. When the aircraft was level, the horizon was at eye level. The screen was 38 cm wide and viewed from 38 cm resulting in a horizontal optical size of 53.1 deg. The image of the road was always symmetrical but the horizontal location of the vanishing point was continuously perturbed using a sum-of-three-sines forcing function. This resulted in a quasi-random simulated "crabbing" motion of the aircraft beyond the control of the observer and uncorrelated with the vehicle states. The purpose was to eliminate any spurious cues arising from unintended static reference marks.

Figure 2

Examples of Display States



Initial conditions. The experimental design called for four scene classes formed by crossing two levels of the central angle of the road (30 and 60 deg) and two levels of the display sensitivity or gain (-.3 and -.6 deg/ft). Display gain refers to the change in road angle per unit change in altitude. The displays gains are negative because the perspective central angle of the road decreases as altitude increases. The gain and angle requirements uniquely determine the physical roadway width and initial altitude values which in turn are used for computer scene generation. Table 1 presents the values.

Table 1

Initial Conditions

Class	Height ft	Width ft	Road Angle deg	Display Gain deg/ft
A	95.5	51.2	30	-.3
B	47.7	25.0	30	-.6
C	165.0	191.0	60	-.3
D	83.0	95.0	60	-.6

Display changes. The displays changed from their initial conditions as a function of observer pitch controls and simulated vertical gusts. The actual relationship between these inputs and display effects was determined by a simulation of the flight dynamics of an F-16 aircraft flying at 400 knots at a

100 ft altitude. For details see Levison, Zacharias, and Sinacori (1982).

Observer control. The observer controlled the simulated aircraft and hence the display by means of a force stick mounted to the side of an aircraft seat. Only pitch commands were registered.

Forcing function. The forcing function was formed by summing 13 sine waves having the frequencies and zero-peak amplitudes listed in Table 2. If the power at each frequency is spread about its neighborhood, the resulting power spectrum is a good approximation to the power spectrum of an average vertical gust of 7.7 ft/sec (Levison, Zacharias, & Sinacori). A unique gust was used on each trial by randomizing the phases of the components. An example is pictured in Figure 3.

Table 2

Vertical Gust: Sinusoidal Components

Frequency		Amplitude
cycles per 102.4 sec	rad/sec	ft/sec
3	0.184	1.41
7	0.430	1.74
17	1.043	2.05
23	1.411	1.81
31	1.902	2.31
47	2.884	2.85
67	4.111	3.01
89	5.461	3.47
131	8.038	3.87
179	10.983	4.02
263	16.138	3.95
359	22.028	3.65
521	31.968	3.39

Procedure

The observer's task was to keep altitude constant during the course of each simulated flight. An alternate conception of the task is that it involved compensatory tracking of the central roadway angle. This task is interesting in that, once a trial began, no reference angle was presented: An observer tracked his or her concept of what 30 or 60 deg looked like.

Each flight or trial began with 15 sec of viewing the static display corresponding to the initial scene of one of the four conditions. A ready signal was then given and both the gust and force stick were activated. The dynamic phase lasted 120 sec of which only the last 102.4 sec were used as data. At the end of each trial, the observer's mean, standard deviation, and RMS height error were displayed. Four trials, one for each condition, constituted a session and observers ran for two sessions a day. Conditions were uniquely randomized within each training session, and were further

constrained to form a Latin Square over the last four sessions (16 data trials). These began when an observer reached an asymptote based on RMS height error.

Results

Basic data. The 102.4 sec scoring interval was sampled at 40 Hz yielding 4096 data points per time series which is sufficient for obtaining power spectra across the frequency range used in sculpting the gust spectra. Basic data include time histories of the gust, control stick force (the observer's action), and height errors. As an example, Figure 3 presents a short record of these time histories for one trial. Notice that the gust has a zero mean but the height error does not.

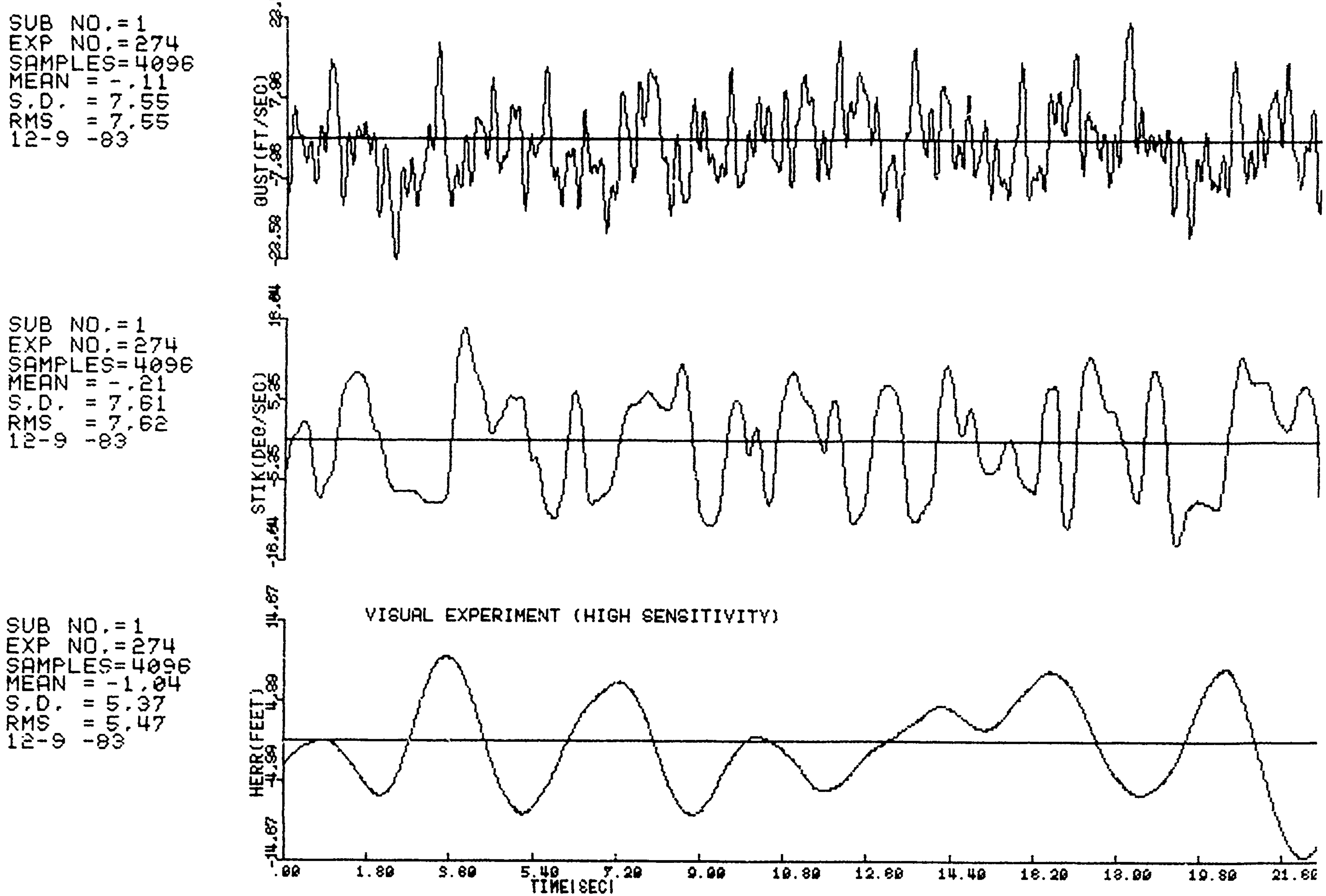
Constant and variable errors. The mean and standard deviation of the height error are indices of constant and variable tracking errors. Figure 4 plots these for the last 20 trials of one condition for one subject and shows that, on average, constant errors are almost zero. This indicates that it is indeed possible to track a non-visible or memorial target. There is however a consistent variable error. This pattern is generally true across all observers and conditions.

RMS height error. The distance from the origin to a point in Figure 4 is the vector sum of the constant and variable errors and corresponds to the RMS height error, our main dependent variable. The grand mean RMS height error was 11.7 ft. A repeated measures analysis of variance (6 observers X 4 test sessions X 2 angles X 2 gains) indicated that neither session nor roadway angle nor any interactions not involving subjects had a significant effect although road angle did account for 4.5% of the variance (10.4 ft at 30 deg versus 12.0 ft at 60 deg).

Display gain was significant, $F(1,5)=11.19$, $p<.05$, and accounted for 13% of the variance. The mean RMS height error was 12.5 ft at a gain of -.3 deg/ft and 9.9 ft at -.6 deg/ft. The conclusion is that "livelier" displays result in lower RMS height errors. This is reasonable: The same altitude error produces a bigger visual effect in a higher gain display than in a lower gain display and hence may permit more rapid detection and accurate correction.

RMS roadway angle error. If the task is viewed as one of tracking the roadway angle, the the effects of gain are even more pronounced but reversed in direction: The RMS angle error was 4.83 deg overall, 3.80 deg at -.3 deg/ft gain, and 5.85 deg at -.6 deg/ft gain. The difference is significant, $F(1,5) = 101.2$, $p<.01$, and accounts for 36% of the variance, a threefold increase over that accounted for by RMS height error. The greater predictive power of gain for RMS angle error over RMS height error may be that display gain is a function of both height and road width as is RMS angle error. RMS height error ignores road width.

More interesting than the difference in effect magnitude, is the reversal of effect direction: The higher gain produced the lower RMS height error but the higher RMS angle error. The effect of gain on tracking performance depends on how the tracking task is characterized! Characterizing the task as angle tracking places emphasis on the status of the (intermediary) imagery rather than on the status of an observer-environment relationship. The situation here


SUB NO.=1
EXP NO.=274
SAMPLES=4096
MEAN = -.11
S.D. = 7.55
RMS = 7.55
12-9 -83
GUST(FT/SEC)
SUB NO.=1
EXP NO.=274
SAMPLES=4096
MEAN = -.21
S.D. = 7.61
RMS = 7.62
12-9 -83
STIK(DEG/SEC)
SUB NO.=1
EXP NO.=274
SAMPLES=4096
MEAN = -1.04
S.D. = 5.37
RMS = 5.47
12-9 -83
VISUAL EXPERIMENT (HIGH SENSITIVITY)
HERR(FEET)
.00
1.80
3.60
5.40
7.20
9.00
10.80
12.60
14.40
16.20
18.00
19.80
21.60
TIME(SEC)
Figure 3

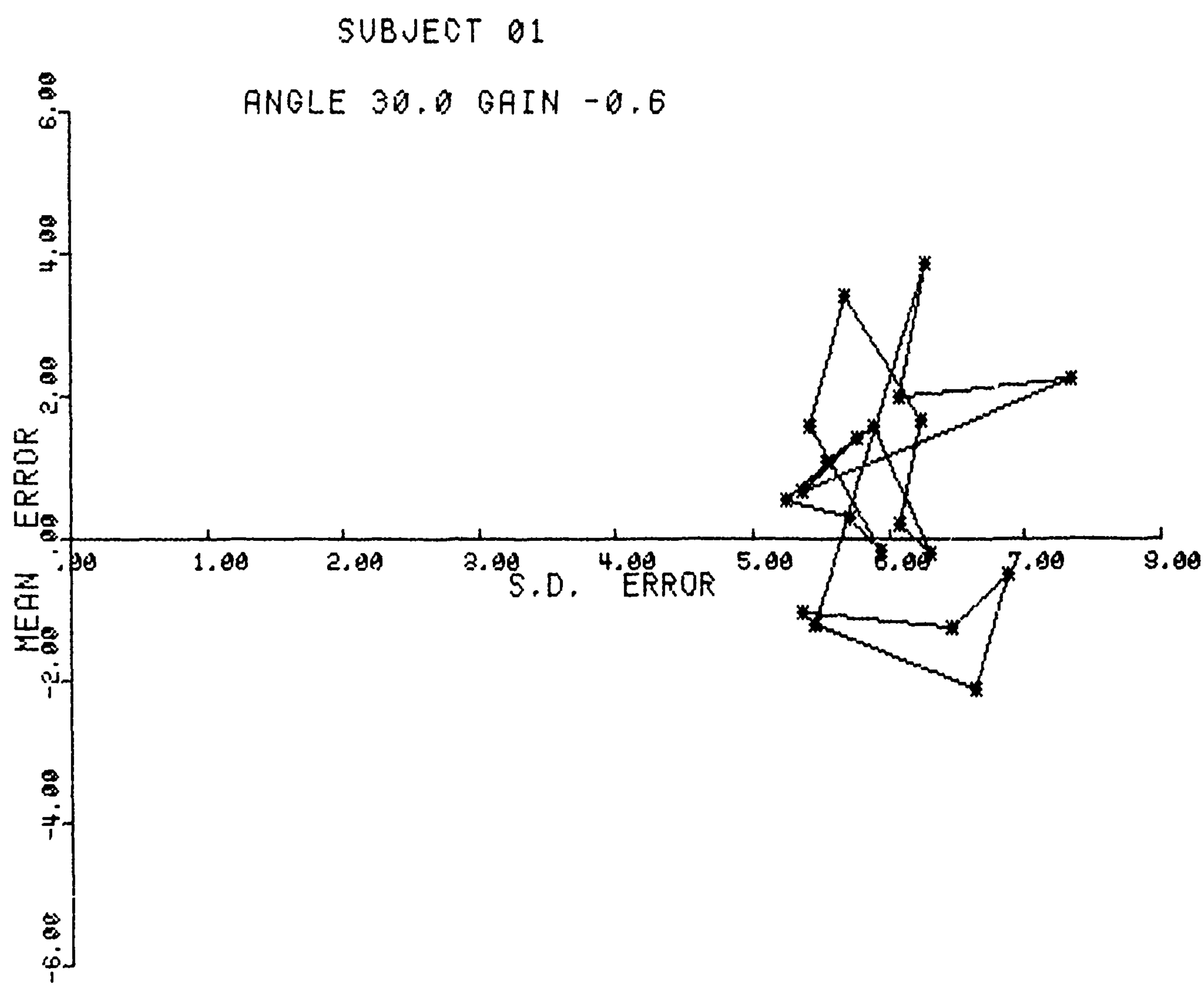

SUBJECT 01
ANGLE 30.0 GAIN -0.6
MEAN ERROR
S.D. ERROR
6.00
4.00
2.00
.00
-2.00
-4.00
-6.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00

Figure 4

reflects the difference between sensory and ecological approaches to perception. What matters in flying is absolute altitude and not the perspectival effects. Our results indicate that observers are in tune with the environment even though they appear to make greater errors with respect to the appearance of the display.

This not to say that imagery is not important. Imagery is crucially important as a conveyor of information. Display gain does capture the fact that the same environmental change can have a different perspectival effect depending on the altitude.

Describing function. Mean square error, like variance and signal power is partionable into orthogonal components. The orthogonal components of interest here are not the experimental factors but rather sinusoids. Power spectra and phase characteristics of the various time series were obtained by using Fourier analysis. Although power may be revealed at any frequency, we are especially interested in those frequencies comprising the gust. The phase lag and the ratio of the "output" power (the observer's control action) to the "input" power (gust or display) at the gust frequencies indicates how well the gust (or display) "drove" the observer's action. A driven action, although phase shifted and amplitude adjusted, is correlated with its driver. Any action not correlated with the input cannot be considered driven and is called "remnant".

Figure 5 presents two examples of the average describing function for one observer at one condition. The vertical bars indicate one standard deviation over four trials. "Stik" refers to the observer's force stick pressure and "gust" is the forcing function. Gain and phase data are only presented at frequencies for which the correlated power is at least four times the remnant power in that frequency region (i.e., >6 db signal/noise ratio). The data in Figure 5 demonstrate that this observer tracked with higher gain at middle and upper frequencies when provided with the -.6 deg/ft display sensitivity than with the lower sensitivity (note the scale differences in the graphs). This observer also produced more remnant at middle and upper frequencies under the high display sensitivity condition. Although difficult to see in the graphs, the observer also generated more phase lead (or less phase lag) at most frequencies with the higher gain display. The gain and phase results, but not the remnant data, are generally indicative of better tracking performance with the higher senitivity display.

Summary and Conclusions

This experiment illustrates the usefulness of using dynamic interactive imagery for the study of altitude control. Interactive imagery, however, poses data analysis problems not encountered in research with static imagery. We suggest that a new experimental methodology, active psychophysics, be developed. A key feature of active psychophysics is that an observer may manipulate a display to seek information necessary for activity in the environment. Just as observers are not always passive, so also the environment is not totally passive and waiting to be exploited. It can bite back. This reality offers another key to the study of real world performance, namely, the use of forcing functions to goad observers and to enable revealing data analysis. We have given examples of these techniques in assessing altitude cues.

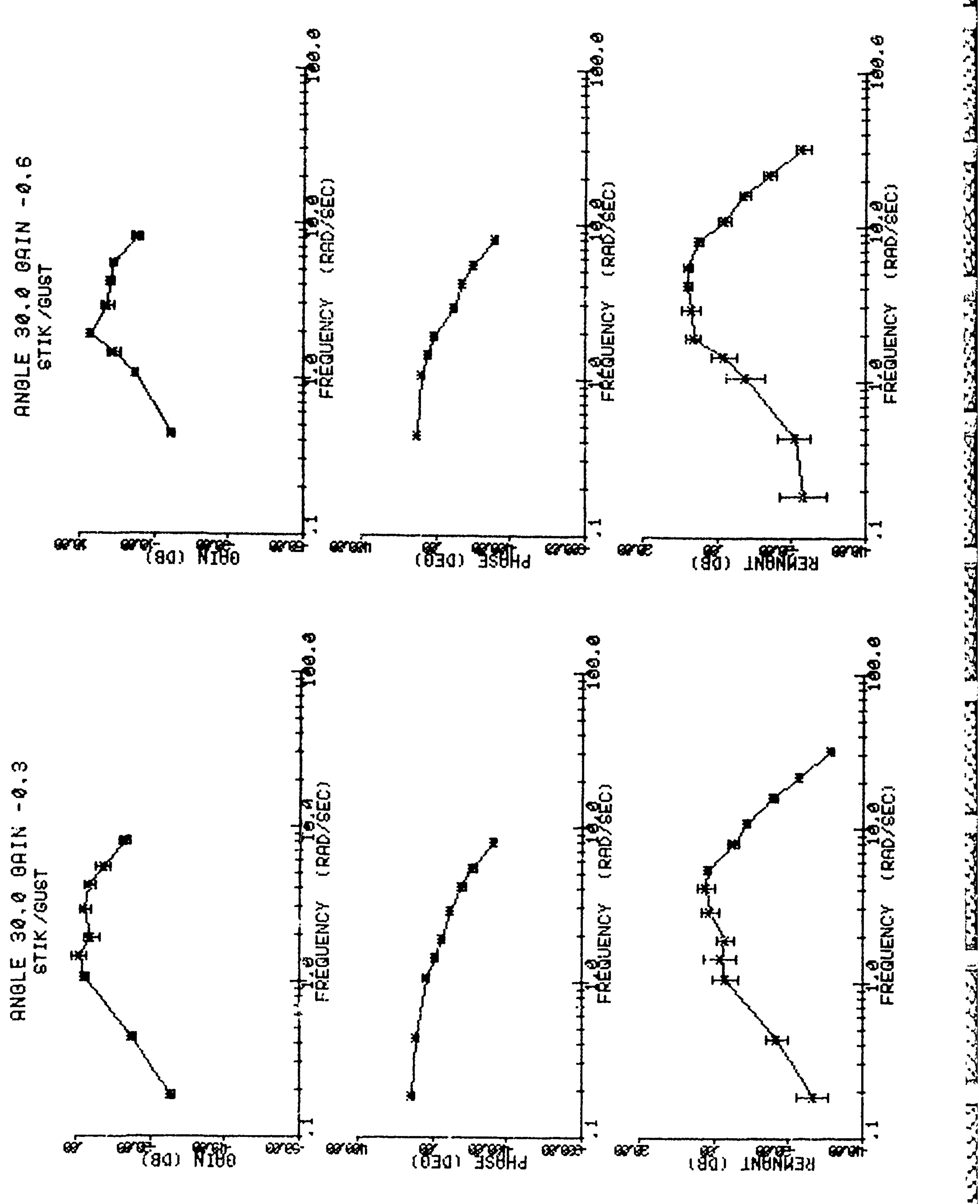

ANGLE 30.0 GAIN -0.3
STIK/GUST
GAIN (DB)
PHASE (DEG)
REMNANT (DB)
FREQUENCY (RAD/SEC)
ANGLE 30.0 GAIN -0.6
STIK/GUST
GAIN (DB)
PHASE (DEG)
REMNANT (DB)
FREQUENCY (RAD/SEC)

Figure 5

Our goal is not only to rank order cues but to assess generative models of their use such as the Optimal Control Model of Zacharias and Levison (1980). Models involve parameters, and a further challenge for active psychophysics is how to relate passive perception indices with those of active performance.

Active psychophysics is more than tracking skills revisited. Not all skilled seeking of information involves tracking nor is all information used for tracking. But many tracking tasks are perceptually demanding and thus offer a place to begin the study of perception-action. A key problem is to develop the right displays for the right tasks.

Acknowledgments

We would like to thank Matt Middendorf for his simulation development support and Teresa McKelvey for her programming and general experimental support. Their performance was outstanding.

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LOW ALTITUDE HIGH SPEED FLIGHT SIMULATION USING VIDEO DISC TECHNOLOGY

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John Terry Hooks, Jr. obtained his MS in mechanical engineering from Southern Methodist University, Dallas. His 30 years of professional experience has been in industry and in the military. Most of the 25 years of his association with LTV Aerospace and Defense Company has been in various aspects of Flight Simulation. He has been the principal investigator in the R&D effort that led to the developemnt of CAPTV concept and the FLIR simulator and is currently on the simulation project staff at LTV Aerospace and Defense Company.

Dan C. McGuire is an aerospace engineer at the Air Force Human Resources Lab, Operations Training Division, Williams Air Force Base, Arizona, with primary responsibility for exploratory development of image generation and display devices for flight simulation. He holds a BS degree in aeronautical engineering from Purdue University and a MBA degree from Arizona State University.

LOW ALTITUDE HIGH SPEED FLIGHT SIMULATION USING VIDEO DISC TECHNOLOGY

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ABSTRACT

The LTV Aerospace and Defense Company's visual technology uses video discs as direct access and storage devices of video data obtained from a series of discrete photographs of the gaming area. Each discrete photograph is electronically scanned, converted to video data, formatted and stored on video disc. When needed for display, the data is retrieved from video disc, processed and manipulated to display the correct perspective view of the terrain relative to the position and attitude of the simulated aircraft. The pilot has complete freedom of route and attitude within the gaming area.

Extensions to the basic video disc technology are currently under development to provide visual simulation of low level tactical missions. This paper describes the algorithm modifications and hardware/software design issues involved in real time generation of low-level/high-speed scenes. Descriptions are also provided of a non-real time emulation of the concepts and hardware design.

1.0. INTRODUCTION

The successful development of a real-time training capability for Forward Looking Infrared (FLIR) sensor systems in 1980, using LTV Aerospace and Defense Company's video disc based visual scene simulation technology [1] was followed in 1983 by a full color out-the-window visual simulator [2]. Both systems have been incorporated into the Navy's A-7E Weapons System Trainer (WST).

The basic concept employs an array of aerial photographs covering the gaming area defined by pilot training requirements. Photography is needed along straight parallel tracks. These photos are scanned, formatted and stored in a bulk storage device such as video discs. As the student pilot "flies" through the photos using controls similar to the ones on the cockpit panels, they are retrieved from the storage medium for display. At any given instant, based on the pilot's eyepoint in space, the photo in the data base nearest his location is stretched, skewed, rotated and translated in a piece wise, continuous mathematical transformation such that the transformed photo overlays a different photo taken from the pilot's eyepoint. This is a continuous process occurring during each frame time under computer control. It allows the introduction of smooth translation into a basically still picture set. During the period in which motion is taking place using a given fixed scene, the computer is retrieving a new appropriate view to be used as an overlay substitute. The new view is selected using a prediction scheme that determines when the present photo must be discarded in favor of a new photo. Transitions can be made from photo to photo within a track, across tracks and across altitude shells with equal ease, providing complete freedom of movement for the pilot within the gaming volume. The key feature of the approach is its ability to make one fixed photo serve in a dynamic translation long enough to retrieve another view.

The two major subsystems of the Company's Visual System are the Record Processor System (Figure 1.1) and the Image Generation System (Figure 1.2). The Record Processor System scans the source photography, digitizes the resulting video, corrects the brightness, contrast and color of the digital video, formats the high resolution scan into NTSC standards and records the video on analog video tapes. These tapes are eventually mastered on video discs and serve as the data base for the Image Generation System. The Record Processor System is also used to generate a digital data base for every photograph.

The Image Generation System consists of the Video Storage System, the Video Digitizer System, the Scene Storage System, Cell Processor Systems and the Visual Computer. The Video Storage System consists of several video disc player units. Any randomly accessed TV frame on a single unit can be located and made available within a few seconds. The Video Digitizer System converts the analog output of the video discs into a digital stream and performs other formatting functions. The Scene Storage System is a large semi-conductor memory capable of storing a high resolution scene. The Cell Processor system receives the digital video data of a given scene from the Scene Storage System, and under computer control selects the portion that is visible to the pilot through one window, performs the geometric transformation as required by motion of the pilot's eyepoint and generates the color video signals for the display. Refer to 2 for further details on the basic Visual System concept.

2.0. LOW-ALTITUDE/HIGH-SPEED REQUIREMENTS

The Company's visual concept treats all pixels in a snapshot as having been imaged onto a single two-dimensional plane. This approach is appropriate for a substantially flat terrain where natural texture of the photography will to a large extent provide relief cues. However, the technique may not be satisfactory for high-speed low-altitude flights over high contoured terrain with significant relief. The essential subjective effect of the present system will be the loss of parallactic fidelity for non-planar terrain features. From a training point of view, it is important to project with correct parallax the major contours of the terrain (such as mountain ranges, large clump of trees, rows of buildings, hangars, etc.) with particular attention paid to targets and target areas.

The present system uses an aerial photographic density based on trade-offs in resolution and data base costs, applicable to high altitude (750 ft. and above). However, low-altitude/high-speed flight over high-relief terrain demands attention to several new considerations such as speed of access from the video discs, much shorter time intervals available between photographs, significant resolution changes in generated imagery due to large amounts of scene interpolation, the need to provide realistic smearing as a function of the elevation angles, the size of the data base, etc. Finally, during the evolution of a hardware system for use with low-altitude/high-speed regime emphasis is placed on the retention of as much of the present hardware as possible in order to minimize cost.

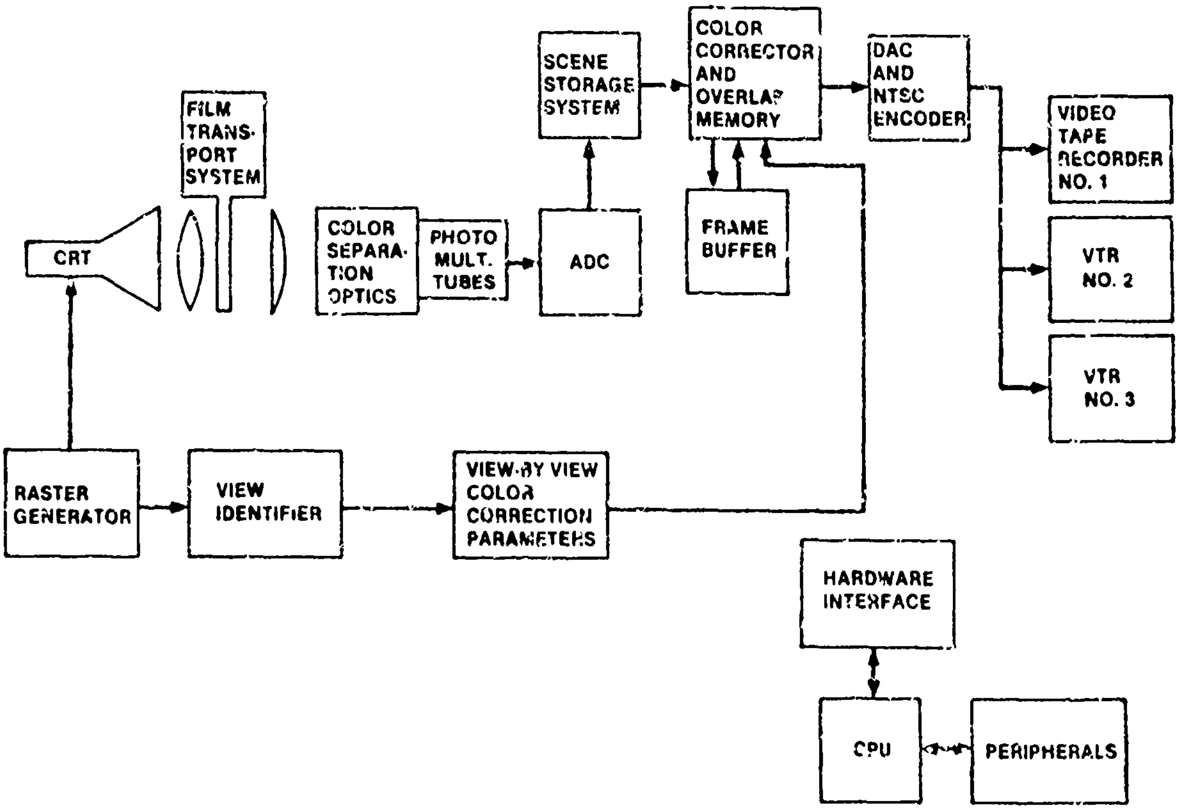

Figure 1.1 The Record Processor System

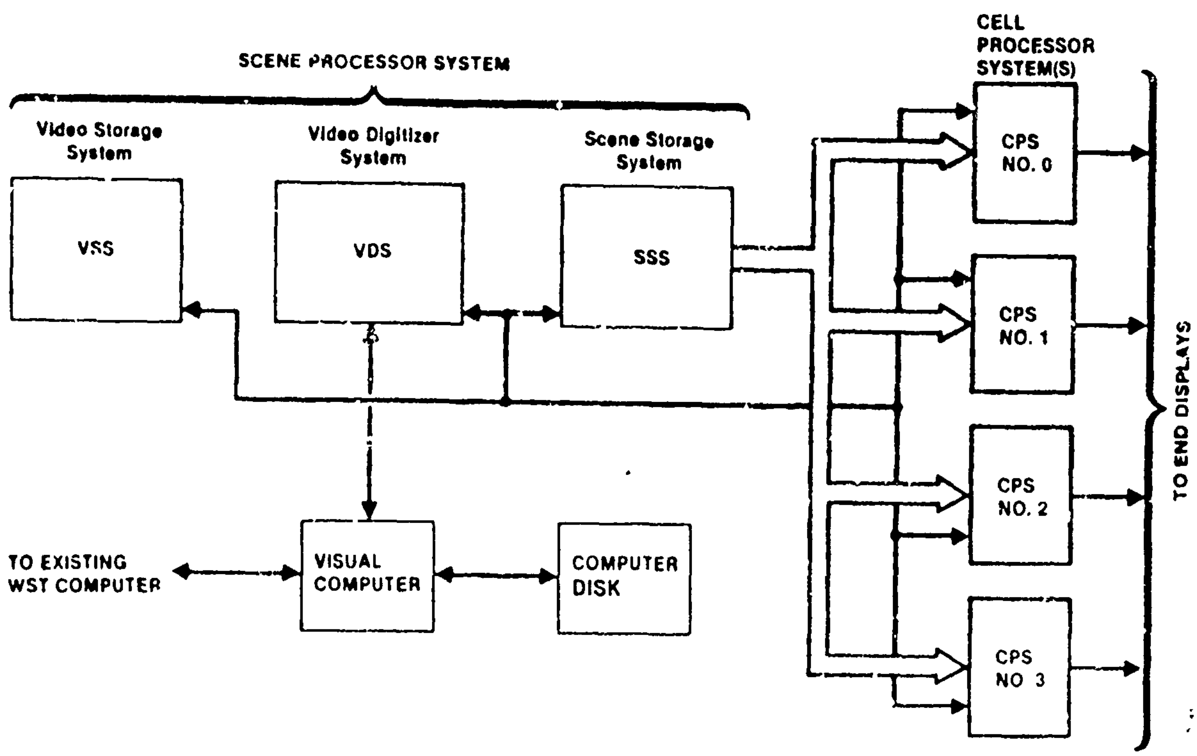

Figure 1.2 The Image Generation System

The factors mentioned above motivated a Phase I conceptual study of the features of a video disc based system that would satisfy the needs of the low-altitude/high-speed flight simulation. In the folowing section, we describe some of the concepts developed during this study.

3.0. SEPARATE REGION MAPPING

An animation algorithm can vary from a whole picture mapping function to a complex transformation computed for each individual pixel. The methodology of each selected algorithm has cost and complexity consequences which must be balanced against the larger eyepoint volume gained for each picture. Separate Region Mapping (SRM) offers a compromise in complexity while providing the necessary capability of parallactic fidelity for selected terrain features. In this method, region boundary detectors are used to partition in real-time a given window of display into separate regions each of which is identified as having isolated feature boundaries, orientation and range. Examples of such separate regions in typical training scenarios include clumps of trees, buildings, poles and runways. During display each separate region is mapped with unique orientation and perspective transformation matrices. It must be emphasized that in the simulator, real-world photographic detail will be contained within each separately mapped region and no additional computing time will be involved in generating this detail. Thus, a fairly small number of regions will suffice to provide both parallax and scene realism.

3.1 Hardware Implications of SRM: The Record Processing System [2], used for scanning and recording the high-resolution photographs does not need any modifications to implement SRM. Additional scene descriptor parameters must be created for each scene that relates separate regions in a given scene to separate regions in all possible neighboring scenes, to which a transition may be required.

The image generaion system requires hardware modifications to implement the SRM technique. Figure 3.1 illustrates the major elements of the image generation system with the modifications required for SRM shown with hash marks. The number of regions required to map a typical low altitude scene is a function of terrain relief of major importance to training scenarios. It is felt that 64 regions per window per scene will suffice for the intended natural and cultural relief.

Separate mapping of regions must be accompanied by filling-in of small areas on the display adjacent to the separate regions. These are areas which would have been mapped by the separate regions if they had been treated as part of the background terrain. Several approaches exist to implement a low pass fill-in filter algorithm. A Phase II study will determine the most appropriate technique from a subjective criterion. It must be emphasized that the fill-in areas constitute a very small percentage of the total image area.

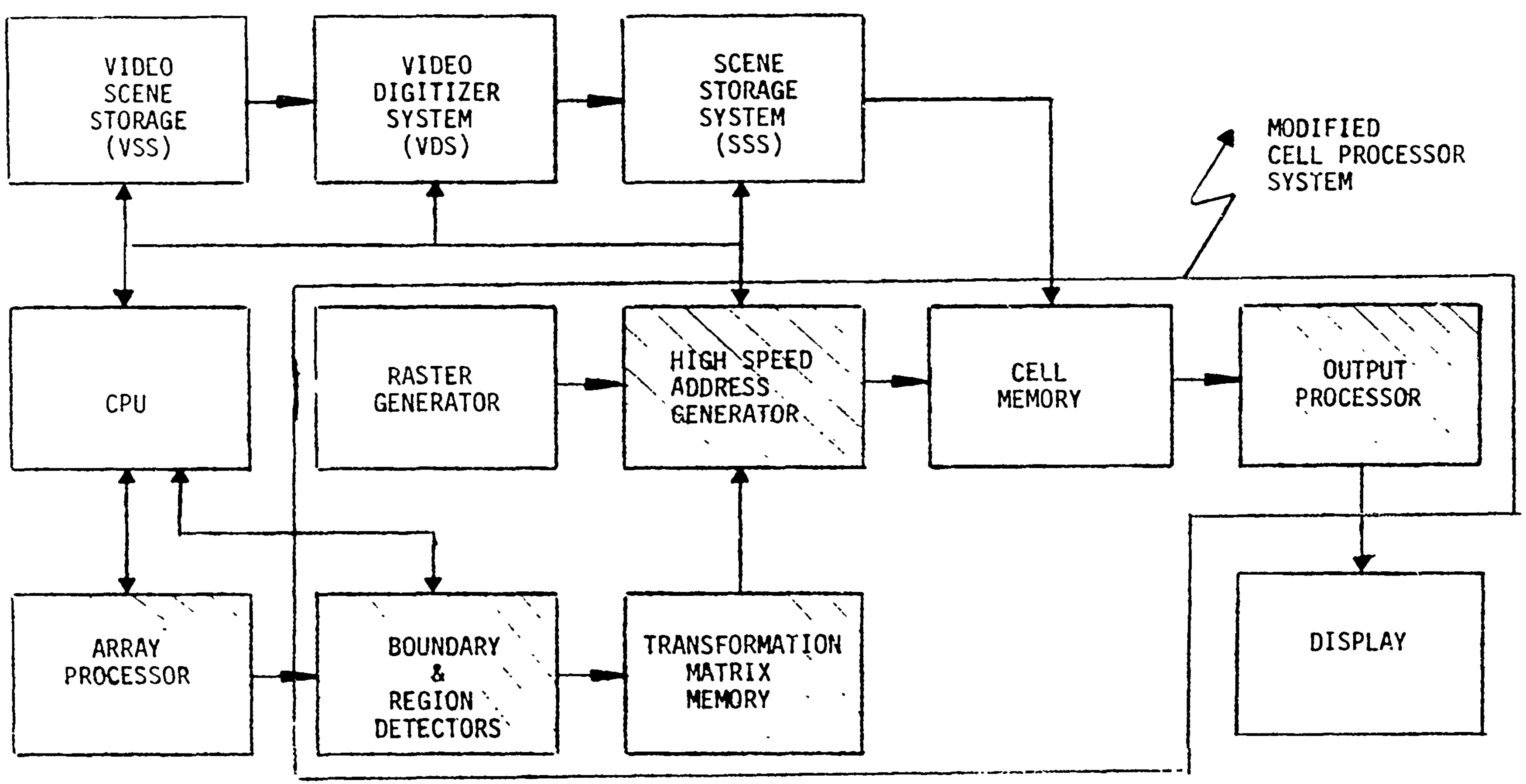

Figure 3.1 The Image Generation System with Modification for SRM.

4.0. STUDIES ON PICTURE SPACING

In the image generation system terrain images obtained at discrete points in space (camera points) are used to form simulated images that correspond to the terrain viewed from other points in space (eyepoints). For each camera point there is a domain over which it must be used to generate the simulated imagery. The size of the domain of each camera point then determines the number of camera points required to form the data base for a fixed gaming volume. One of the fundamental questions to be answered is how far can a camera point be stretched. In order to answer that question, one must first determine how the simulated image quality varies as a function of eyepoint/camera point (EP/CP) geometry. The specific performance parameters of interest are resolution, deviation of vertical objects from the vertical and occulting/disclosure of objects. Further, for a high-speed/low-altitude penetration aircraft, e.g., B1-B, the angular rate of motion (w) of terrain imagery below the aircraft can be quite high, greater than 1 radian/sec. This effect is referred to as "smearing" and allows somewhat lower resolution imagery to be used for some portions of the viewing area.

4.1 Resolution Change Compensation: As a simulated aircraft is flown through the gaming volume represented in the data base, the eyepoint will successively move through the domains of camera points. In general, the eyepoint will be in front of the camera point before a camera point transition and will be behind the camera point after transition. In Figure 4.1, this corresponds to EP1 and EP3, respectively, where EP3 represents the condition just prior to transition and EP1 represents the condition just after transition. At the transition, the EP/CP geometry shifts suddenly resulting in a sudden change in resolution. In order to minimize this effect, it is desirable to modify the data stream after the transition point so that the resolution increase is spread over several frame times and, therefore, is less noticeable to the observer.

It is well known that resolution in digitized imagery is related to the horizontal and vertical fractional bandwidth[1] of the video. Therefore, the proposed technique of compensating for transition is to temporarily reduce the video horizontal and vertical fractional bandwidth of the luminance data using a time varying two dimensional digital filter. The filter bandwidth will be increased over several frames so that the resolution change will be gradual. The maximum bandwidth of this filter will correspond to the horizontal and vertical fractional bandwidth at the earth's horizon.

In figure 4.2, a block diagram is shown which illustrates the Cell Processor System with the proposed resolution compensation filter. The shaded blocks are new. The bandwidth computation block determines the compensation filter bandwidth as a function of raster coordinates. The output from this block is then used to determine which filter coefficients should be provided to the digital filters. The filter coefficients will be computed off-line and stored. The bandwidth computation block will operate at 1/3 the pixel rate, i.e., the required bandwidth will be computed every

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[1]Fractional bandwidth of a digital signal is the ratio of the original analog base bandwidth to half the sampling frequency.

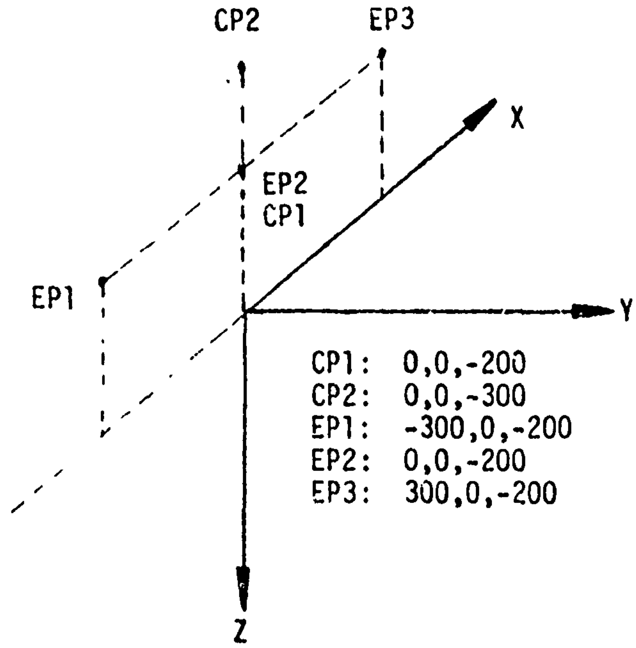


Figure 4.1 Eyepoint and Camera Point Coordinates

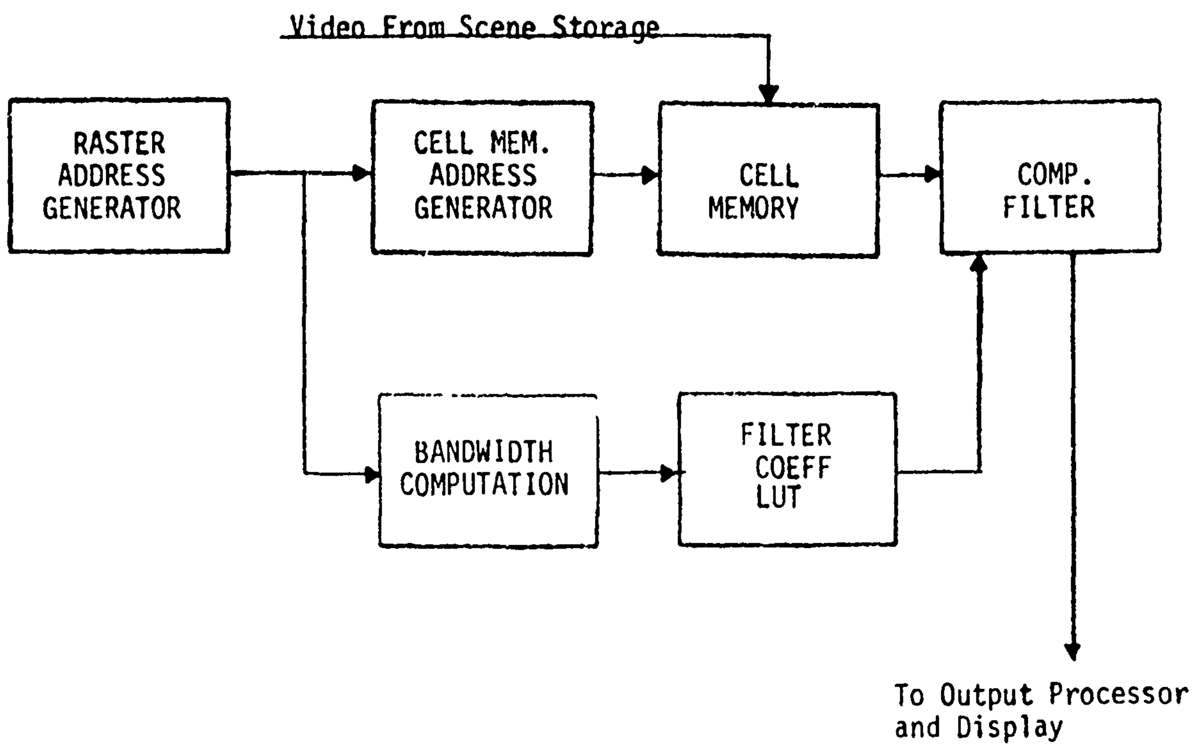


Figure 4.2 CPS With Compensation Filter

third pixel. The compensation filter itself will be composed of two sections. The first section will filter the video in the vertical dimension. The second section will filter the video in the horizontal dimension.

4.2 Resolution Estimator: In order to control the bandwidth of this filter, it is necessary to find a simple mathematical function that can be used to estimate resolution change, and therefore, the required bandwidth. The function chosen is a range ratio: Beta = R_{EP}/R_{CP} where R_{EP} is the range to a point on the ground from the simulated eyepoint and R_{CP} is the range to a point on the ground from the camera point.

Beta was used as the resolution estimator and constant Beta contours on the ground and on the photo plane were plotted for various eyepoint/camera point geometrics such as EP1/CP1, EP3/CP1, EP1/CP2, EP2/CP2 and EP3/CP2. These plots helped establish the range of Beta on the photo plane. However, in the A-7E WST visual system, video for each display window is generated by one CPS. The resolution change profile is different for each window since the EP/CP geometry is different for points observed through each window. Therefore, the constant resolution contours were mapped into the display window to determine the variation of resolution within each window. In Figures 4.3 and 4.4, the Beta diagrams for the six display windows are shown for CP2/EP1 and CP2/EP3. In Figure 4.3 it can be seen that in window one, the value of Beta is always greater than one which indicates improved resolution. In windows four and six, the value of Beta varies from 0.75 to 1.05 which indicates that the resolution will be improved in some areas of the window and degraded in other areas. In Figure 4.4, the resolution is degraded in all windows. Worst case Beta variations were established which resulted in the determination of the parameters of a digital FIR filter system to be incorporated into the output section of the CPS.

At this point, we consider the smearing phenomenon and its bearing on the image resolution issues discussed above.

4.3 Smearing: Based on experiments on human sensory perceptions 3 , it has been determined that an object appears to be blurred or smeared when the angular velocity of the line of sight vector to the object (w) exceeds one radian/second. For scenarios where the aircraft speed is high (approximately 1000 feet/sec.) and the altitude low (approximately 200 feet), the angular rate of terrain imagery can exceed 2 radians/sec. for large portions of some windows. In order to illustrate the phenomenon, constant angular velocity contours are shown in Figures 4.5, for 0.8, 1.0 and 1.2 radians/sec. The shape of the contours in aircraft coordinates depends only on V/H (velocity/height of the aircraft). From this diagram, it may be observed that a significant portion of windows four and six will be subject to smearing. By comparing Figure 4.5 to Figures 4.3 and 4.4, it can be seen that those areas in windows four and six where resolution is poorest will also be subjected to the maximum smearing. Thus, the change in resolution at the transition must be smoothed over in order to provide normal smearing cues. This provides an additional reason for incorporating the resolution compensation filter discussed in earlier sections.

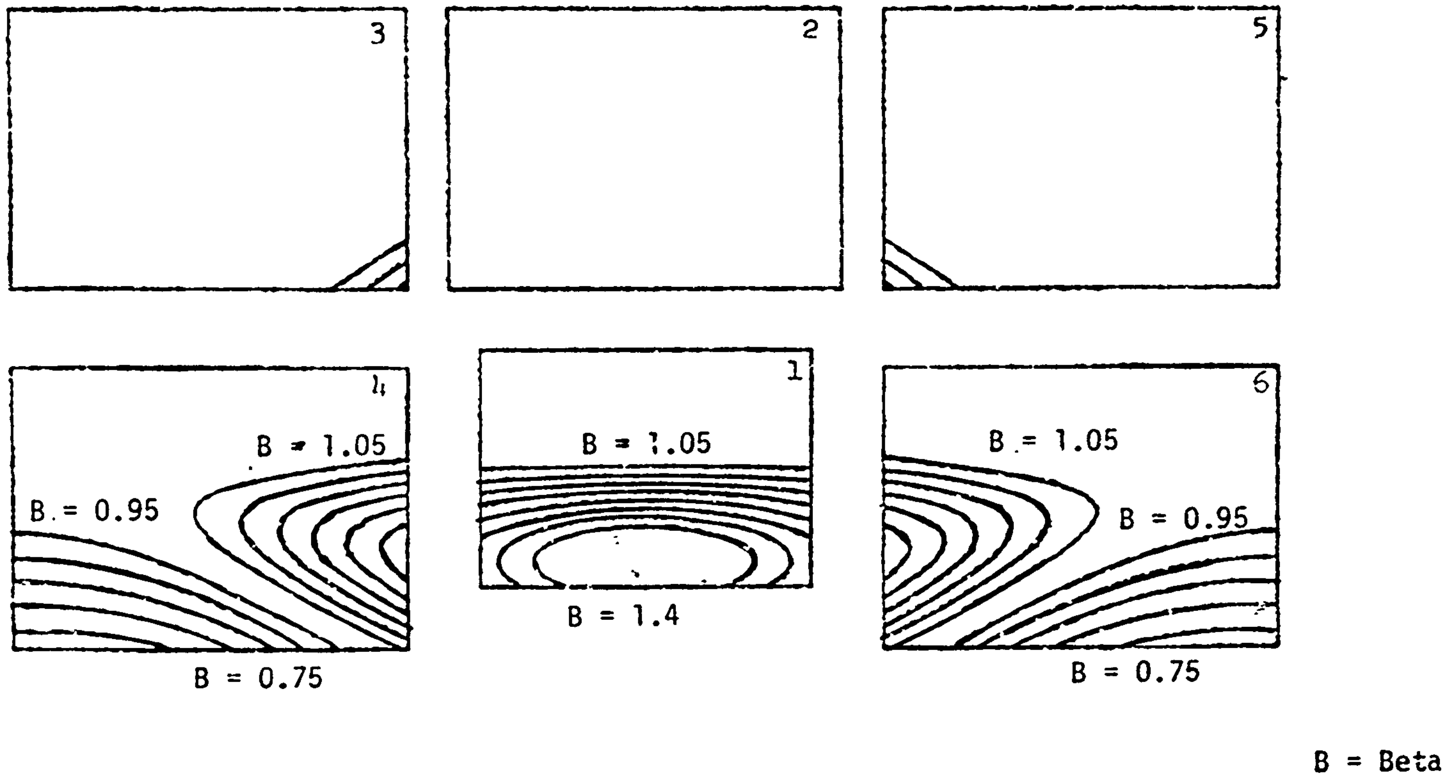
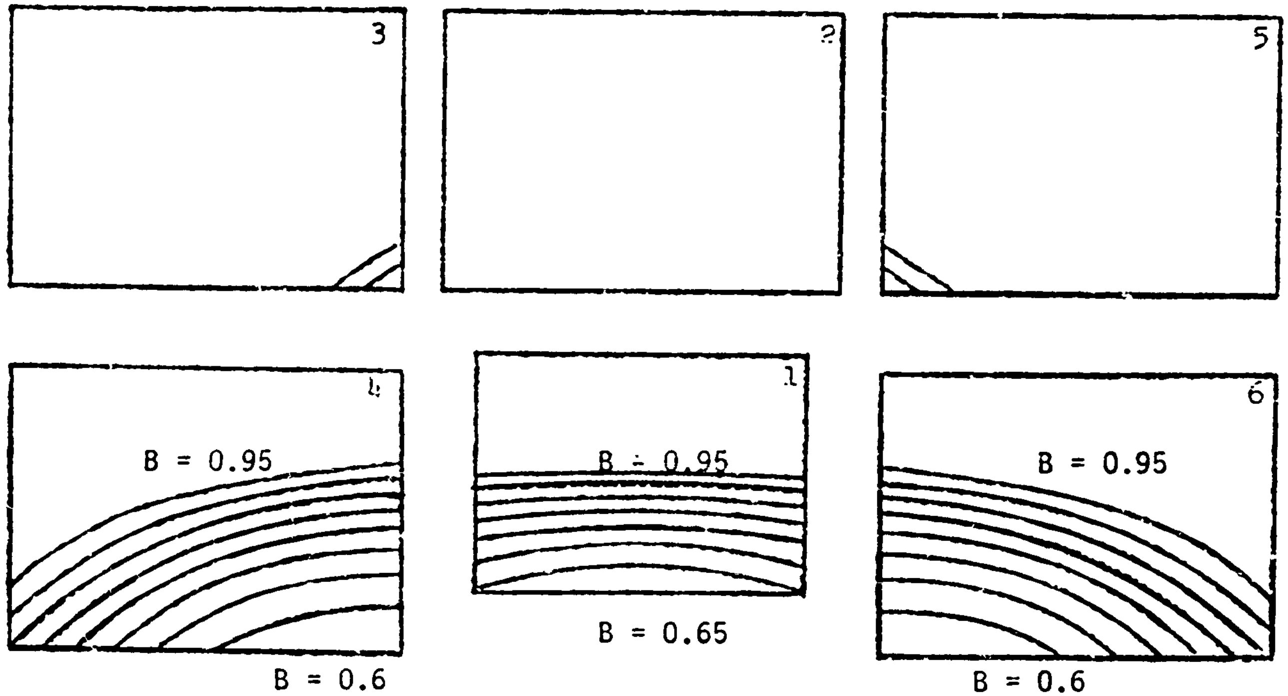


Figure 4.3 Constant Resolution Contours for EP1, CP2



B = Beta

Figure 4.4 Constant Resolution Contours for EP3, CP2

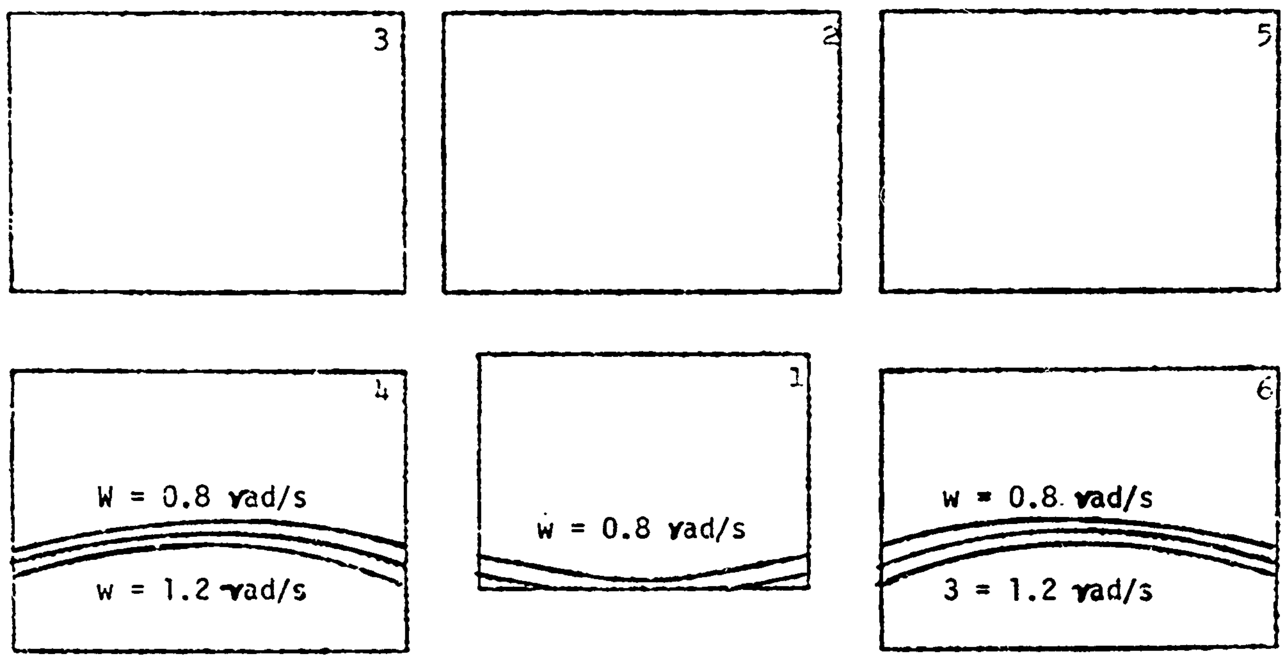


Figure 4.5 Smearing Boudnaries (Velocity = 1000 FPS, H = 200 Ft.)

5.0. NON-REAL TIME EMULATION OF THE LOW-ALTITUDE/HIGH-SPPED CONCEPTS

The various techniques described and a few others related to low-altitude/high-speed flight simulations are incorporated in a non-real time emulation presently underway at LTV Aerospace and Defense. An actual B-52 low-altitude training area was photographed, scanned and digitized on the Record Processor System to serve as a realistic data base for this emulation. The separate region mapping and compensation filtering algorithms were coded in software on a VAX 11/780 and Grinnell Image Processor System, and a typical scenario was generated frame by frame. Subjective evaluation of the resulting film clip will help confirm the concepts developed under Phase I study and answer a few important design questions.

6.0. CONCLUSION

In the study reported here, we have focused on the techniques of solving some of the specific problems arising out of the application of a video disc-based visual system to the simulation of low-altitude/high-speed navigation. Several analytical studies were carried out resulting in practical hardware designs. The Phase I concepts are being validated with a non-real time emulation under a Phase II contract. These studies will help develop a complete data base plan for a specific training scenario which together with the hardware-software specified in this report can result in a viable low-altitude/high-speed visual system.

7.0 REFERENCES

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(3) J. L. Brown, "Sensing Systems, Chapter 4 of Best & Taylor's "Physiological Basis of Medical Practice", 9th Ed., p. 8-63 to 8-120.

SESSION II

Environmental Data Base Considerations
Part I

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Colonel Blake attended the U.S. Naval Academy, Annapolis, MD, graduating in June 1958 with a bachelor of science degree and his Air Force commission. In 1967 he graduated from Southern Methodist University with a master's degree in industrial/engineering management. Col Blake is a 1974 graduate of the Industrial College of the Armed Forces, Fort Lesley J. McNair, Washington, D.C.

In July 1958, Col Blake entered primary pilot training at Bartow AFB, FL, and attended basic pilot training at Greenville AFB, MS. After attending basic instructor school at Craig AFB, AL, he returned to Greenville AFB as a T-33 instructor pilot. With the closing of Greenville AFB in 1960, he attended T-37 instructor training at Craig AFB and was assigned to the 3525th Pilot Training Wing at Williams AFB, AZ, as instructor pilot/check pilot in T-37 and T-38 aircraft. He was next assigned to the 13th Tactical Bombardment Squadron, Clark AFB, Philippines, as a B-57 pilot flying 288 sorties over Southeast Asia from May 1965 to October 1966.

After graduating from SMU, Col Blake attended the Air Force Test Pilot School, graduating in 1969. Upon completion of KC-135 upgrade training at Castle AFB, CA, in April 1969, he went to Wright-Patterson AFB, OH, as a test pilot in the Directorate of Flight Test (Bomber Operations Division). In May 1971 he was assigned to the A-X System Program Office as Chief, Test and Development, assisting in evaluation [illegible] and A-10 close support fighters. After graduating from the Industrial College of the Armed Forces in 1974, Col Blake went to Nakhon Phanom Royal Thai AFB, Thailand, serving as executive officer to the 7th Air Force vice commander and as Chief, Operations Plans Division. In August 1975, Col Blake began four years of duty at Headquarters, U.S. Air Force in Washington, D.C., serving the last 33 months with the F-16 program as the program element monitor, Deputy Chief of Staff, Research and Development, and Special Assistant for the F-16, Office of the Assistant Secretary of the Air Force, Research, Development and Logistics.

From July 1979 to June 1980, Col Blake served as vice commander of the 384th Air Refueling Wing (H), McConnell AFB, KA. From June 1980 to July 1981, he served as commander of the 384th Air Refueling Wing (H), McConnell AFB.

In July 1981, Col Blake was assigned to Wright-Patterson AFB, OH, as the F-15 System Program Director, Deputy for Tactical Systems. Col Blake assumed his present position in December 1982.

AD-P004 313

SIMULATING SPEED AND HEIGHT CUES IN THE C-130 WEAPON SYSTEM TRAINER

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Major Sieverding has been a practicing navigator since 1971 and an instructor/evaluator since 1974. He has 4000 flying hours, with over 400 hours in combat. He holds the Distinguished Flying Cross and several Air Medals. In 1981, and again in 1983, he was chosen by USAF Chief of Staff as the USAF nominee for the Institute Of Navigation technical achievement award. He has published numerous technical articles in professional navigation periodicals and has given presentations before technical groups in both the United States and Canada. For the last several years, as a member of the MAC C-130 SIMCERT Team, Major Sieverding has been instrumental in the development and refinement of the C-130 WST visual system.

SIMULATING SPEED AND HEIGHT CUES IN THE C-130 WEAPON SYSTEM TRAINER

The C-130 Weapon System Trainer (WST) at Little Rock AFB, Arkansas is, perhaps, the most realistic full mission simulator in DoD. Much of its realism and training value comes from the ability of its full color, CGI visual system to provide speed and altitude cues while flying low level over a "real world" visual data base (VDB) of more than 50,000 square nautical miles. The C-130 aircraft is navigated visually while flying at approximately 250 knots and 300 feet above the ground. Visual ground references in the C-130 WST must realistically reflect chart information and provide the visual cues necessary for confident flight above the ground contour. This paper describes various types of speed and height cues and highlights the major attributes of the C-130 WST visual system that give these cues during a typical C-130 WST mission profile.

Many internal conclusions and observations are admittedly subjective...based on several years of system use and thousands of hours of flying time...and not confirmed by hard data from the behavioral sciences community. The rate of technological change has far outpaced our ability to quantify its impact on human factors under controlled and statistically sound conditions. Those offices with the authority to procure and apply new simulator technology are quite reasonably hesitant to provide funding without such proof. However, the presumed benefits of using new technology can sometimes outweigh the risk of using that technology without analytic proof of its benefits. Funding actions may at times be the result of intuitive judgment and visceral reaction, but full acceptance and application of new technology requires analytic proof of its impact on human factors. This paper includes several open questions and personal conclusions regarding human factors that may raise some eyebrows among readers. The author welcomes any data that supports or rejects internal conclusions or answers the unanswered questions.

Identifiable Versus Stylized Cuing at the Speed of Height

To a stationary observer in a rotary wing aircraft only identifiable objects of known dimensions give height cues, there are no speed cues. In fixed wing aircraft each iteration of the visual senses not only identifies objects, but also notes their change in location or dimension with time. All objects, identifiable or not, are height cues if the speed is known. Conversely, all objects, identifiable or not, are speed cues if the height is known. Many aircraft, including C-130s, fly nearly constant groundspeeds during low level missions. Previous experience and the reinforcements of instrumentation and instruction tell the pilot what rate of change to expect from objects at a given speed and altitude. If the rate of change does not meet expectations, the pilot will climb or descend to the target altitude. Consider two pilots, each highly proficient at flying 300 feet above the ground contour using visual references in hilly terrain fairly void of cultural features. One pilot has been flying C-130s at 250 knots, the other has been flying F-111s at 450 knots. If both pilots were to suddenly switch aircraft, the F-111 pilot would fly the C-130 at considerably less than 300 feet, the C-130 pilot would fly the F-111 considerably higher. The pilots would fall victim to their anticipated rate of change of objects not fitting their new speed profile...even though some identifiable features of known dimensions may have been present. With experience and reinforcement they could realign their anticipated rate of change of objects with their new speed profile and regain 300 feet proficiency, but not before causing

their wingmen or ops officers considerable anguish.

This powerful cue of the observed change in objects from a moving aircraft can be gained through the use of non-identifiable, stylized objects under certain conditions of density and naturalness. These objects may include point features, two dimensional co-planar areal features, or three dimensional features. The required degree of object density would change with different speed and altitude profiles. The required degree of naturalness would satisfy the pragmatically inspired necessity of aircrew acceptance without exceeding it. What are these required conditions? Exceeding them unnecessarily increases system acquisition and maintenance costs, and could delay program milestones. Not meeting them foretells program failure and wasted money at best; negative training at worst. And let's not ignore identifiable objects and the valuable out-of-the-window cuing reinforcement they provide. Identifiable objects are generally more complex than stylized objects and may require additional system capacity and VDB generation manhours. What degree of identifiable versus stylized objects is required? What if real world topography does not contain identifiable objects? Should a "real world" visual system minimize these cues to present a realistic challenge?

In some cases the sole reliance on stylized features to provide speed and height cues would be preferred over the artificial addition of (for example) a house to every hill...where none exists in nature...especially in a visual system that possesses numerous types of speed and height cues that react synergistically to the observer. Although false cues (my term) can have advantages, it detracts from the mission realism that has been painstakingly designed into every other aspect of the full mission simulator. False cues unnaturally focus the aircrew's attention and raise the ever present specter of aircrew rejection. New technology has given us enough system capacity so that false cuing advantages do not outweigh the risks.

Atmospheric Perspective

Atmospheric perspective has been used by artists for six centuries to give depth to paintings. A distant object will have less of its true color and more of the atmospheric haze color than a close object because of the atmospheric diffusion of the true color with distance. This source of cuing decreases its effect when visibility conditions are increased. It increases its effect when the color/intensity difference between the object and the haze is increased. Atmospheric perspective allows an approximation of relative distance from an object based solely on how much that object has been faded within a field of like objects.

Consider an observer in an aircraft looking at two mountain ridges-one in front of the other. The approximate distance to and between the two ridges can be determined by the fading difference between the ridges and the surrounding environment...the greater the fading, the greater the distance. This intuitively recognized stimulus applies not only to ridges, but to all viewed objects when they are treated with the same, realistic fading algorithm.

The obvious engineering solution for providing this cue is to treat fading as an inverse square of distance. Research of FAA transmissivity tables indicate that flight visibility is equal to that distance where two per cent of the object color remains. Initially, the C-130 visual system treated fading as follows:

$$F = e^{K\left(\frac{R}{Df}\right)} \qquad \text{(EQ.1)}$$

where: F = per cent of face color remaining
$K = \ln(0.5)$
R = range to face (nm)
Df = distance where a face is half faded to haze =

$V_1/(\ln(.02)/\ln(0.5))$

where: V_1 = input visibility (nm)

a more simplified expression would be:

$$F = e^{\frac{-3.912*R}{V_1}} \qquad \text{(EQ.2)}$$

The physics of this solution appears irrefutable, yet experienced C-130 crew members consistently complained that the keyboard input of visibility was not what they saw through the simulator windscreens. An informal test using six subjects in dozens of flight conditions (130 samples) confirmed the complaints. Results indicated that EQ.1 fit tightly with crew response at up to two nautical miles of input visibility. As input visibility was increased over two miles the disparity between perceived and input visibility increased...until 30 miles of input visibility was required to achieve 11 miles of perceived visibility.

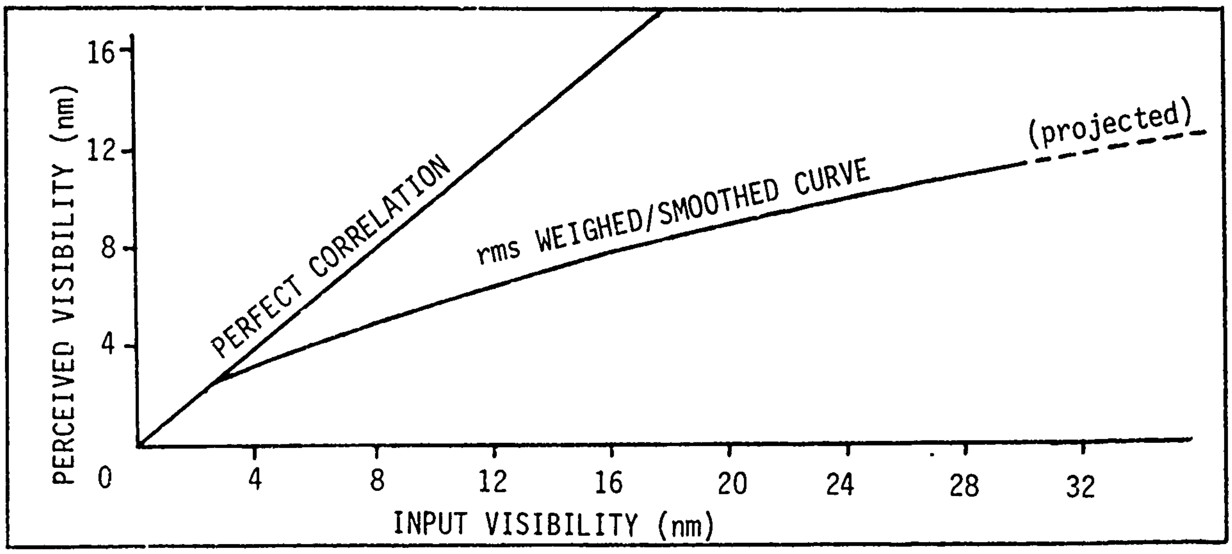

Figure 1

A graph of input to perceived visibility allowed construction of a simplified correction factor for EQ.2 when input visibility exceeded two miles:

$$V_2 = V_1(((V_1-1).16)+1)$$

where: V_2 = corrected input visibility (nm)

and:

$$F = e^{\frac{-3.912*R}{V_2}} \qquad \text{(EQ.3)}$$

The results of using EQ.3 nave been highly satisfactory after a year and a half of operational use in all visibility and ambient light conditions. However, the physical reason for the need of the correction factor is unknown, as is the exact importance of the speed and altitude cues provided by atmospheric perspective. Is it easier for a pilot to fly a constant altitude contour when visibility is equal to one minute of groundspeed than when visibility is equal to ten seconds (or ten minutes) of groundspeed? Under certain conditions of terrain type some restriction of visibility adds to speed and height cues. What are they?

A corollary to atmospheric perspective is color perspective. This artist's technique has also been used in paintings for many centuries. An artist will apply "warm" colors (orange, yellow) to objects he wishes to accentuate or advance, "cool" colors (green, blue) to objects he wishes to diminish or recede. Is this artist's truth applicable to visual flight simulation? Probably, even though some recent data (Kraft, Anderson, Elworth; Proceedings of the Human Factors' Society, 1982) indicates otherwise, but where is the proof?

Texturing

Texturing is by far the most important of those stylized cues mentioned earlier. Texturing allows for a highly dense accumulation of individually discernable, two dimensional, co-planar objects without excessive computational overhead...especially in edge or face limited systems. In the C-130 visual system up to three different modulation patterns of light and dark bands can be rotated (translated) about each other to yield patterns ranging from tartan plaid to (apparent) random abandon. These textures are layered over two dimensional terrain or culture faces and assume the color of the underlaying face, although diminished in intensity. Non-textured faces that are meant to blend into the textured face must use a lower intensity of the same parent color ratio of red, green, and blue. The sensitivities and "tricks" involved in this could easily be the subject of a separate presentation.

C-130 texturing has ten levels of detail. As an observer moves toward a textured face the texture pattern can become increasingly complex as it transitions from coarser to finer levels of detail. This capability minimizes quantization and "busyness" in the far scene where objects appear to move very little per update frame, while accentuating the density of cuing in the near scene where objects appear to move considerably per update frame. The differences between successive texture levels of detail must be small enough to insure that the observer is not presented with opposing cues at different ranges from the face. Although the textured face may look different at different ranges, the texturing cue must be consistent.

The power of texturing as a stylized cue could allow a skilled pilot to successfully maintain a nearly continuous altitude above a single textured horizontal plane without the reinforcements of altitude instrumentation or a discernable horizon, and without the continuous presence of identifiable objects of known dimensions. How long the pilot can maintain this is unknown, but the difference between the performance of this pilot and another pilot flying over a non-textured horizontal plane would be considerable.

Texture modulation patterns must be carefully constructed to insure that they possess an appropriate degree of irregularity and density, or apparent strobing of the texture can occur at closer ranges or higher groundspeeds. This undesirable effect is similar to the apparent backward rotation of wagon wheels during the hectic chase scenes in movie westerns. The faster the update (refresh) rate of the visual system, the less the importance of this concern. This concern becomes more important on visual systems with very wide horizontal fields of view, or flown at very high groundspeeds, how wide or how fast is unknown.

A corollary to texturing is diminishing perspective. As a linear object of constant width recedes to the horizon, its apparent width decreases. The narrower the width, the greater the distance. CGI systems, especially those without circle edge (curve) generation...such as the C-130 visual system...have a good deal more of this cue than what is present in nature. Nature is composed of curves, with the possible exception of crystalline rock formations. Man's cultural overprint on the natural scene has added straight roads, railroads, power lines, hedgerows, and plowed fields. Even in those areas of the world where Euclidean logic is unknown, man has long ago determined that the shortest distance between two points is a straight line and fashioned lines of communication and separation accordingly, wherever the terrain allowed. In densely populated regions or in areas where man has access to labor-saving machines, even the most formidable obstacles to man carry his straight line imprint. In sparsely populated areas the curve prevails and a perception of edges may be non-existent.

Texture patterns must be chosen that suit the level of cultural buildup in specific areas. The modulation and translation of texture bands should be perceived as being linear in areas of cultural development; perceived as being irregular or random in areas void of culture. The intent is not to give the pilot the knowledge that he is flying over a certain population density, but rather to give him a realistic density and composition of cues.

The C-130 visual system was designed without a circle edge generation capability...this is not to be confused with curved surface shading, which the device does have. All edges are straight lines, all texture patterns are composed of straight bands (although they need not be perceived as such). Because of this, the C-130 data base possesses a higher density of diminishing perspective cuing than the real world, at the cost of lessened realism. Was the trade off worth it? Would the addition of circle edge generation be cost effective? Where is the data for proof?

Sun Angle Shading

The C-130 visual system treats the intensity of each face as a function of: 1) the assigned color, 2) atmospheric fading, 3) ambient light condition, 4) verticality of the face, 5) horizontally defined angle between the direction of the face and the direction of the sun for the given ambient light condition. Factors 4 and 5, together, provide the important speed and height cue of sun angle shading. This cue has its foundation in art. Chiaroscuro, or the use of shading to achieve depth in paintings, has been used for centuries. During day conditions, when sunlight effect is not totally diffused by clouds, the sides of objects facing the sun will be brighter than those facing away from the sun. Shadows may be cast. The consistent orientation of these solar cues help the pilot intuitively sense the shape of the terrain beneath him and anticipate the form of the terrain in front of him.

A pilot, accustomed to flying with the setting sun at his back, just topping the crest of a large hill, and suddenly confronted by a brightly illuminated horizontal plain will increase his altitude in response to his recent experience of knowing that rapidly rising terrain in front of him will be bathed more brightly in the setting sun light than gradually rising or flat terrain. The pilot may or may not be able to vocalize why he pulled up; his reaction may or may not have been consciously inspired, but his altitude over that bright field will be higher than that of another pilot who is suddenly confronted by a dimly illuminated field.

The C-130 visual system does not include cast shadows. Under certain conditions of terrain type and sun elevation this cue could become paramount. What are those conditions? The C-130 system displays the same intensity of sun angle shading with or without a cloud overcast. Realistically, the effect of the horizontal component of sun angle shading should be reduced during overcasts. Is this

heightened degree of realism worth a reduction in speed and height cues?

Originally, the C-130 system used the cosine of the angle between the direction of the face and the direction of the sun to determine the horizontal component of sun angle shading. The physics of this solution appears irrefutable, yet the effect of the solution was too much contrast between shadowed faces, and not enough contrast between illuminated faces. The pragmatic solution was to square the cosine of the angle. It worked. Why?...or more precisely, why was the original solution wrong?

Terrain Face Density

The density of terrain faces effects the density of speed and height cues, even in systems with texturing. In the C-130 system, each face can have a different orientation of its overlaying texture pattern, thereby increasing the perceived density of the texture. Atmospheric perspective is enhanced in areas of greater face density. The fading algorithm uses the distance from the computed eyepoint to the face center (centroid) to determine how much the entire face is faded. The greater the face density, the smoother and more natural the fading becomes. Sun angle shading also becomes more natural and effective.

The C-130 visual system has a multiple level of detail (LOD) data base. An automated transformation program takes DMA Level 1 terrain data in 60X48 arc minute blocks and divides each into twenty 12X12 arc minute regions. Each region is divided into 64 triangular faces for the coarsest LOD; 1024 triangular faces for the finest. The area of each triangle in the most detailed LOD averages less than one eighth square mile. The C-130 system has five densities of terrain LOD. The transformation program integrates numerous factors, including the vertical development of the terrain, when it determines the size and position of the terrain triangles within a region. Faces become smaller in hilly areas.

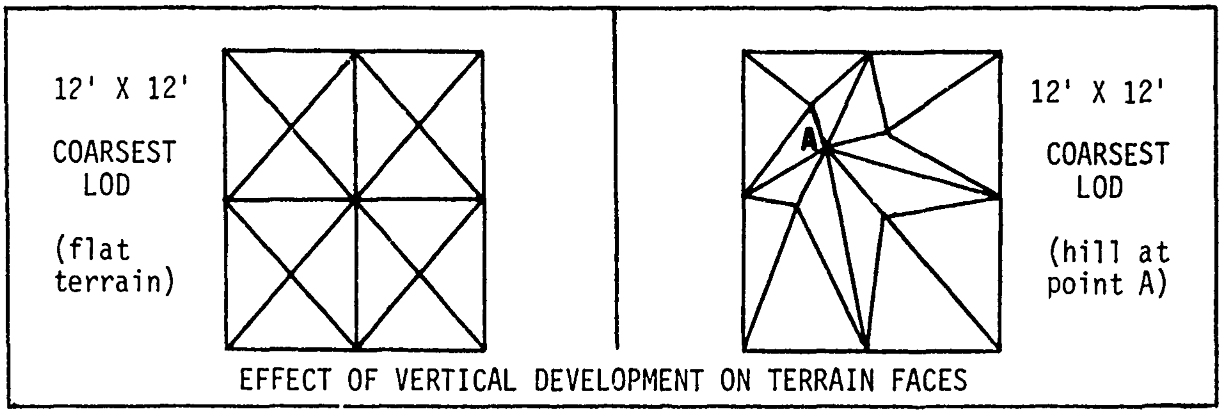

Figure 2

Figure 2 illustrates the effect of vertical development on terrain face distribution for the coarsest LOD region. The finer LODs add additional vertices and subtend additional faces based upon elevation codes within the DMA source data. Each vertice can be assigned a different elevation value.

As the observer moves through the VDB, the terrain transitions from the coarsest LOD in the background to the finest LOD in the foreground. The range at which the LODs are activated is variable. The C-130 system has a dynamic load control that alters LOD activation ranges as a function of local scene content and allows the display of a fairly constant scene density. LOD radii are contracted in extremely dense local scenes, expanded in sparse local scenes.

Although an exact minimum and maximum has not been established because of the many variables that alter LOD radii and the very large size of our VDB, the

activation radius for the coarsest LOD in the most detailed region of the data base with three formation aircraft present is near 15 miles. The radius increases to nearly 30 miles in the least detailed regions with no formation aircraft displayed. The formation aircraft are modeled in multiple LODs to minimize useless edge consumption and extend maximum display range.

When the WST is flown single-ship, or as lead in a formation, the primary consideration is the display of navigation cues because visual navigation is the primary training task. When the WST is flown in-trail behind (up to) three formation aircraft consuming hundreds of edge crossings, terrain radii may be contracted...but formation integrity is the primary training task. As a general rule, dense local scenes have more close-in navigation cues than sparse local scenes, where the only navigation cues may be mountains near the horizon. The effect of contracted radii on navigation cues in dense local scenes is normally in the noise level.

The use of a dynamic load control rather than a variable refresh rate offers significant advantages. The constant 30Hz of the C-130 visual system allows minimal strobing of both the formation aircraft and the terrain. Strobing, caused by a slow refresh rate at high groundspeed and low altitude, destroys the eye's perception of apparent motion of objects and the valuable cue it affords.

The average edge load on the C-130 visual system is less than the maximum of 8192 (advertised as 8,000 for those people who believe in round numbers) because of the need for the system to respond rapidly to newly activated, highly dense LODs without exceeding frame time and causing gross scene irregularities. A mean value would be near 7,000 edge crossings. Selected areas of the VDB, such as developed airfields and intensive training locations, require special modeling "tricks" to prematurely activate high density, long distance flight cues. The impact their activation has on dynamic load control is considerable, and requires the system to normally run with extra capability in its hip pocket.

The world of CGI is stuck with faces and edges...curved or straight...textured or not...until Mandelbrot (fractals) and filtering mathematics can be applied to a new DMA source, providing us with a natural data base; and VLSI or its progeny can compute and display it at 60Hz on a display system capable of 24 arc <u>second</u> resolution. Waiting for this futuristic fantasy may take a lifetime. The cost of total realism could be extreme. What degree of realism is required? This is an old question still in need of an answer. Perhaps the only answer is to boldly and confidently embrace new technology, implement it on a grand scale, and determine analytic proof of its benefits afterwards. The risks of such action are enormous. An <u>exact</u> definition of required realism will never be gained, but it can be approximated. This approximation must use objective analysis as its basis. How do we get there from here?

Mea Culpa

Papers presented before technical symposiums typically <u>answer</u> questions and communicate successful solutions to acknowledged problems. This paper, with its proliferation of questions to challenge the sciences and disturb the issues, is obviously <u>not</u> of that genre. Many of the questions have been answered in an isolated sense, but none of them have been answered within the synergistic environment of the C-130 WST. The study of an isolated portion of the many cues for speed and height (or any other type of subset cuing that exists within a full mission simulator) is not valid when certain cues serve as catalysts and the total cuing is greater than the sum of the parts. Such is the case with the C-130 WST. This paper has not even broached on the impact of tactile and aural cues on speed and height perception. Definitive answers to all of my questions, within the dynamic context of a full mission simulator, will be very challenging

to obtain. As technology changes, the quality of full mission simulators will change with it. The previous rules that defined human inflight perception may be negated, or at least become questionable. The questions themselves may be changed at the last moment by an historically fickle user driven by a dynamic technology on the aircraft and avionics side of the house.

Widescale acceptance of improving simulator technology within DoD is inevitable. The cost advantages and enhanced combat capabilities of full mission simulation will become impossible to ignore. When?

The key issues are confidence and application. Technology is driven by so many factors in our society that it cannot be stopped. Venture capitalists on the corporate side of the house will sense the profit. With my experience in the C-130 WST I can sense the application and the confidence, the technology and the profit will take care of themselves.

PRODUCING HIGH SCENE CONTENT WITH PERSPECTIVE VALIDITY

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Geoffrey Y. Gardner received his PhD in Electrical Engineering from the Polytechnic Institute of New York in 1976. He has an A.B. from Harvard College and an M.S. from Adelphi University. Dr. Gardner has been with Grumman Aerospace since 1960, and is currently head of the Computing Sciences Branch at the Research and Development Center. He has been principal investigator of the Computer Image Generation project for 8 years. Previous research in advanced applications of computers included the analysis of stress electrocardiograms and the identification of bullets. Dr. Gardner is a member of Sigma Xi, IEEE, ACM, and SIGGRAPH.

Robert S. Rulon received his B.S. degree from the State University of New York at Oswego in 1953. He has spent 28 years at Grumman in training and training systems. He has been associated with the Grumman Advanced Computer Image Generation program since 1977 and was program manager for the Air Force Human Resources Laboratory sponsored Advanced Visual/Sensor Simulation Study. His responsibilities have included systems engineering in a number of Grumman trainer programs and proposal efforts including A-6E Weapons System Trainer and F-14 Operation Flight Trainer. During the Apollo program, he was responsible for requirements definiton and contractor interface for the Lunar Lander Mission Simulator Visual System.

PRODUCING HIGH SCENE CONTENT WITH PERSPECTIVE VALIDITY

by

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ABSTRACT

Maintaining perspective validity in visual displays is essential to providing proper training cues. Perspective validity has many aspects, including correct perspective transformation of geometric shapes, exact determination of surface priority relationships, accurate shading of curved as well as planar surfaces, consistent mapping of texture patterns onto scene surfaces, and proper representation of aerial perspective. This paper describes the mathematical models used in Grumman's non-edge computer image generation CIG technology to maintain perspective validity in all its aspects.

INTRODUCTION

The need for realism in aircraft out-the-window visual displays has yet to be quantified, as such studies are expensive, the necessary experimental equipment may not exist, and cueing requirements vary widely for different training goals. By examining typical training tasks we can formulate a number of cueing requirements and from them deduce many of the requirements for the visual system for use in training. Parameters such as field of view and minimum resolution can be quickly quantified. Other visual system requirements can be established only after more lengthy analysis of cue utilization.

Ground attack, a maneuver commonly assigned to most combat aircraft, can serve as a useful example. Figure 1 illustrates ground track and altitude plot during a 10° bomb run. At points on the ground track aircraft pitch and roll are noted. Figure 2 shows the target track as seen by the pilot through the windshield and canopy during the maneuver. It is immediately apparent that the target migrates considerably within the field of view. Figure 3 is similar to Fig. 1 except it is for a 45° bomb run, hence the altitude plot starts at greater altitude with much steeper descent. Figure 4 shows a large migration of the target with the field of view as did Fig. 2 during the shallow descent. Each attack profile will be very similar in requiring this wide field of view, however, the target and objects in the flight path will appear at different aspects even when viewed from the same distance down range.

To practice visual ground attack, the pilot must be able to extract relevant cues from the visual scene. These cues will include those necessary for target acquisition and identification, relative position of target aircraft, relative rates and closure rate. The target must obviously contain

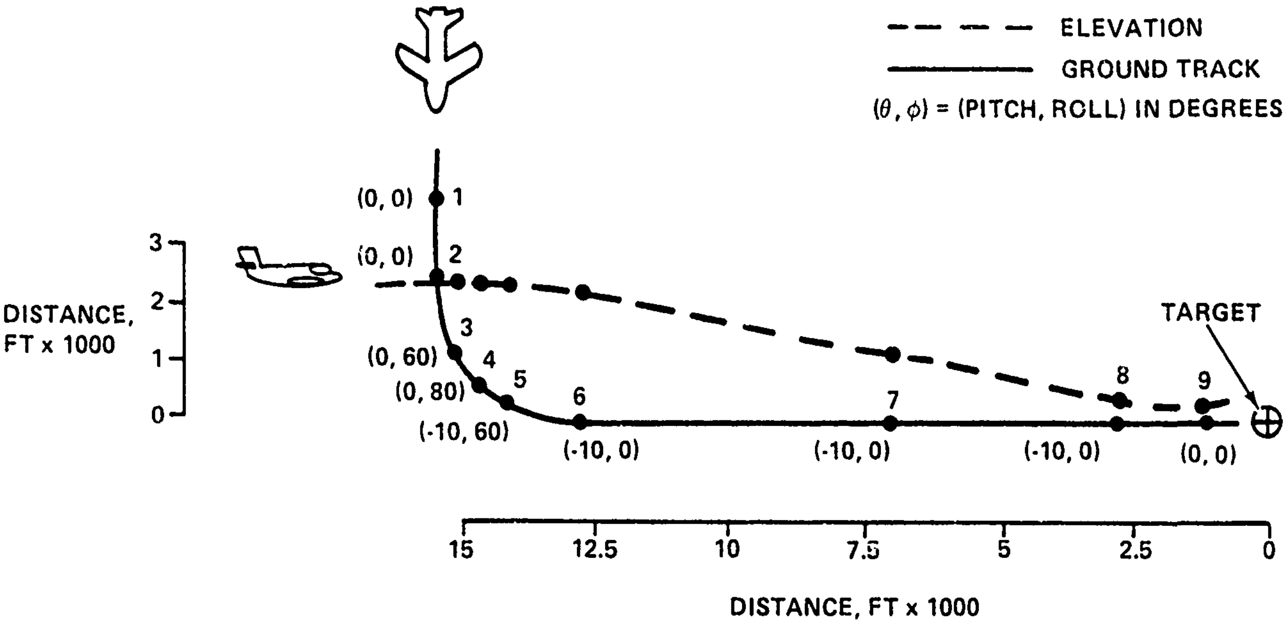

Figure 1 Bomb Run Plot, 10°

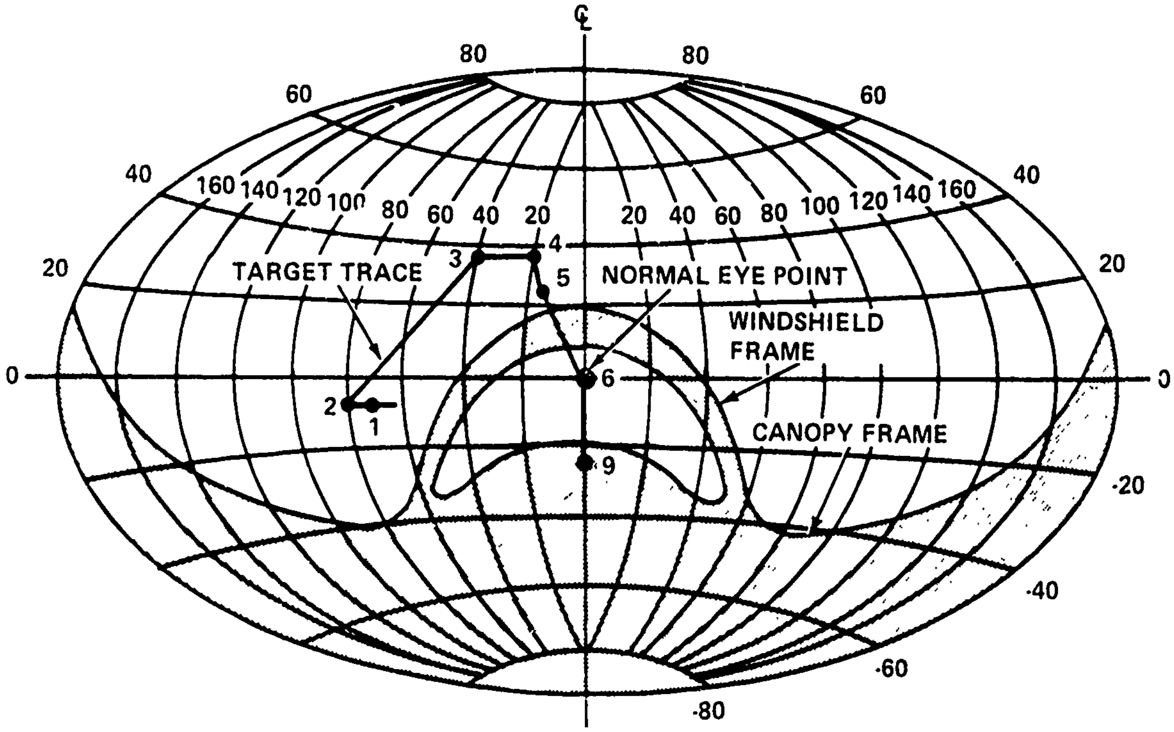

Figure 2 Target Trace, 10° Run

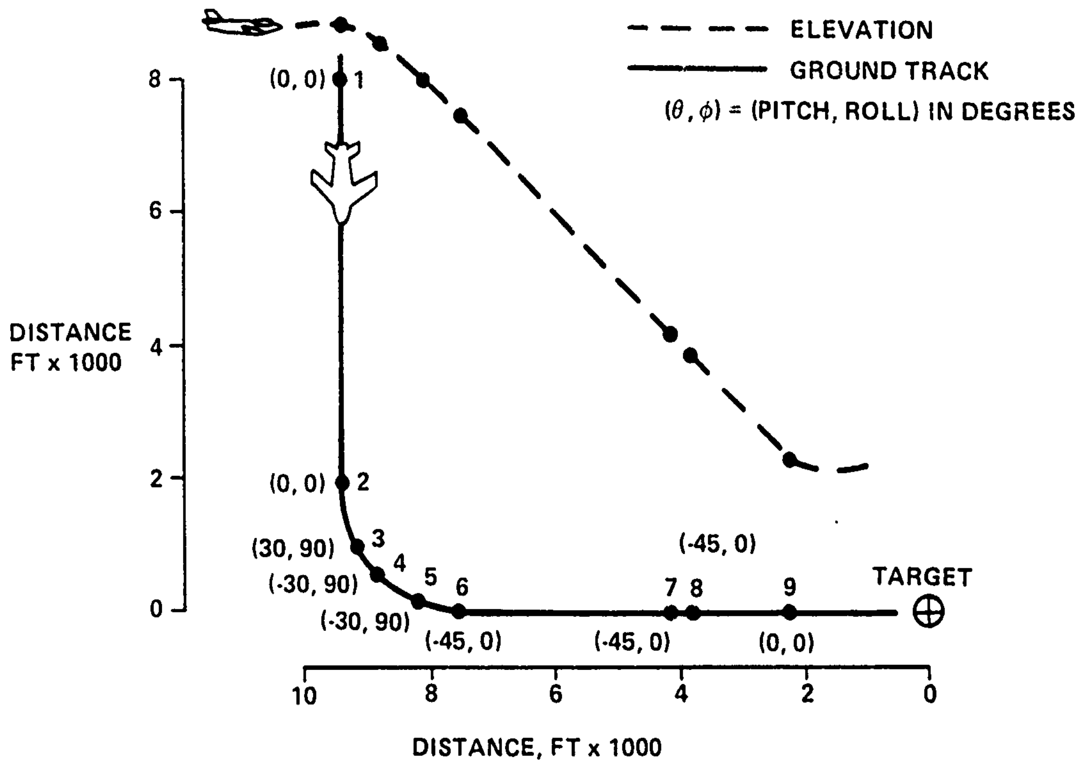

Figure 3 Bomb Run Plot, 45°

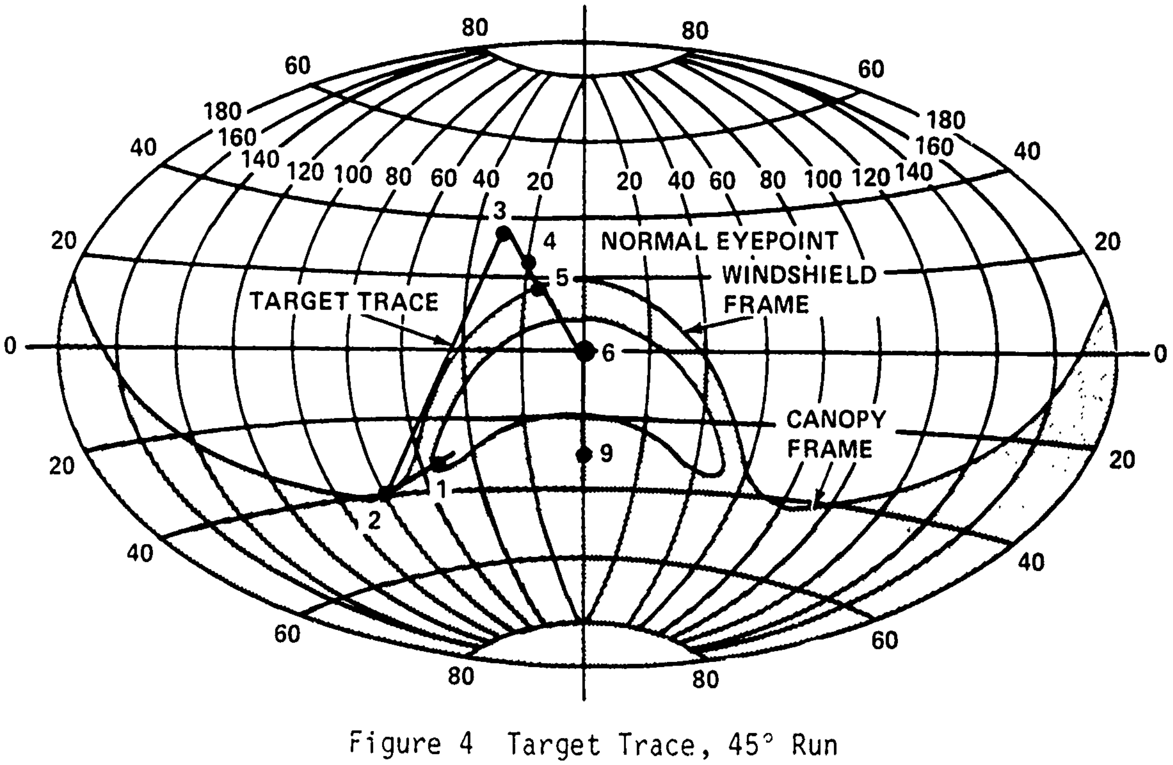

Figure 4 Target Trace, 45° Run

enough detail for recognition and identification at ranges encountered in the actual combat environment. The area about the target is highly important as nearby objects may be prime cues in target acquisition. Should visual target contact be lost through occultation by nearby terrain or other objects or through pilot attention to a simultaneous task, reacquisition will require the target to appear in the expected relative position to nearby objects. Target size, shape and aspect must also relate to the expected appearance from the new viewpoint.

Air-to-ground weapons delivery requires cues to determine initiation of run in to the target, to establish dive angle, to control aircraft velocities, and to initiate weapon release and pull up at safe altitudes. The cues include estimates of closure rates, relative motion and angle of flight path relative to the target and the terrain in the flight path. Simple apparent change in range is an insufficient cue as at longer ranges angular subtense changes very little for relatively large range changes. Increase in object detail also increases slowly with range in the real world, and practical resolution limitations in video displays limit subtle changes in detail with range even more in simulation. The change in apparent relative motion or motion parallax is, therefore, a very strong cue in establishing relative distance. As the eyepoint moves in space, objects move in respect to each other at rates proportional to their relative distance from each other and from the viewer. This change of relative position is of particular importance for rate information at low altitude such as for the 10° bomb run.

These visual cues all require correct instantaneous position of all elements in the scene. This requires the image to be displayed with correct geometric perspective for the instantaneous eyepoint. Correct geometric perspective provides correct object size, shape, occultation aspect, and relative position to other scene elements. Aerial perspective, which is the change in color to blue gray, loss of brightness and detail at increasing ranges due to atmospheric conditions, is an additional cue to estimating range and range rate. Training for less than ideal weather conditions requires the simulation of varying fog, haze and cloud density where the effect of aerial perspective is apparent at relatively close ranges. Other scene elements of importance to formultion of aircraft control judgments include shading and shadows. Shading aids in defining objects, while shadows help tie objects to the surface on which they lie and provide relative height cues.

Not all visual scenes are rich in familiar objects of known size. Large cultivated plains, deserts and tundra are examples of areas that can be very sparsely populated by known objects. Each however, has a distinct surface texture that, when it fills the interspace between objects, can be a strong cue in establishing relative position of objects and hence can help to establish relative rates and closure rates. Computer image generation inherently provides correct geometric perspective because a complete new image is generated for each new display update. Each image will thus include the correct geometry, shading, aerial perspective and texture for the instantaneous eyepoint, to produce the cues required for training in such maneuvers as low level ground attack.

TECHNICAL ASPECTS OF PERSPECTIVE VALIDITY

There are three aspects of perspective validity that are critical to simulator displays. First, the geometry of all scene objects must be presented in proper perspective. For an individual object, each surface must be presented with the proper scale and orientation relative to the instantaneous eyepoint and relative to other surfaces of the object. For multiple objects, each object must be presented with the proper scale relative to all others, and proper occultation of surfaces must be included. Second, the surface shading of all scene objects, including curved objects, must be correct. Third, the environment of the scene must be presented properly and must include proper illumination and aerial perspective.

Maintaining perspective validity presents a problem for simulator displays because of the dynamics of the training environment. The geometry and shading of scene objects generally change dramatically in successive views as the trainee moves through a scene. This is particularly true in low level flight scenarios. In addition, aerial perspective changes markedly as the viewpoint approaches distant objects. Finally, it may be advantageous to repeat training sessions under a variety of environmental conditions simulating different seasons and times of day. Because of this time variation inherent in training, control of the scene data base and image generation process is critical. Computer image generation (CIG) provides this control by allowing arbitrary generation and manipulation of the scene data base and by generating each instantaneous image at the appropriate viewpoint. However, conventional CIG, using planar surfaces bounded by straight edges, sacrifices scene content because the linear scene model is inefficient in modeling the complexity and sublety of real-world features such as terrain, trees and clouds. Our CIG approach reduces the number of scene elements by using a scene model based on curved surfaces and a mathematical texturing function. We have covered the subject of scene content in other publications [1,2,3]. We will now discuss how our approach to CIG provides perspective validity by addressing each of the three aspects of the problem.

Object Geometry

We construct our scene data base in the following manner. We define a three-dimensional scene coordinate space (X_s, Y_s, Z_s), with the X_s axis pointing east, the Y_s axis pointing north, and the Z_s axis pointing vertically up. We define a ground plane $(Z_s = 0)$, an illumination vector, a fractional ambient illumination intensity, and a haze attentuation factor. We define a set of scene "objects," each consisting of one quadric surface and a set of bounding planes, with each surface defined by a set of shape, orientation and position parameters. A mathematical equation is then derived for each surface in scene coordinates. For quadric and planar surfaces, respectively, these equations are:

$$q(X_s, Y_s, Z_s) = q_1X_s^2 + q_2Y_s^2 + q_3Z_s^2 + q_4X_sY_s + q_5Y_sZ_s + q_6X_sZ_s + q_7X_s + q_8Y_s + q_9Z_s + q_0 = 0 \quad (1)$$

$$p(X_s, Y_s, Z_s) = p_1X_s + p_2Y_s + p_3Z_s + p_4 = 0$$

For each two-dimensional image of the three-dimensional scene, an eyepoint and look angle are defined by the current position and orientation of the trainee. We use this information to define a rotation matrix, $\bar{R}$, and a translation matrix, $\bar{T}$, which we use to perform a transformation of coordinates from scene to eye space. If we define the eye coordinates (X,Y,Z) to be centered at the eyepoint (0,0,0), with the Y axis pointing in the direction in which the eye is looking (Fig. 5), this transformation from scene to eye coordinates is represented as:

$$\bar{X} = \bar{R}\bar{X}_s + \bar{T} \tag{2}$$

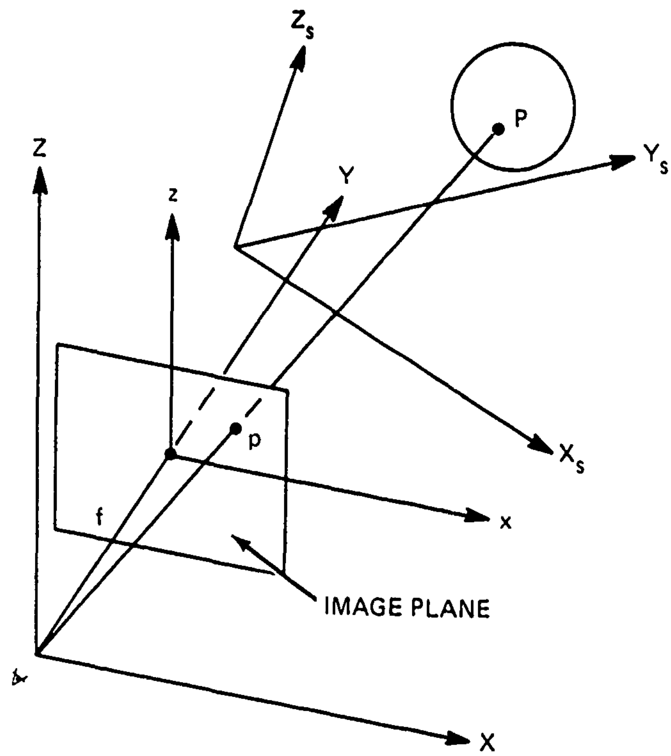

Figure 5 Transformation From Scene to Eye Coordinates and Projection Onto Image Plane

To convert the surface coefficients to eye coordinates we use Eq (1) and (2) to get

$$Q(X,Y,Z) = Q_1X + Q_2Y + Q_3Z + Q_4XY + Q_5YZ + Q_6XZ \tag{3a}$$

$$+ Q_7X + Q_8y + Q_9Z + Q_0 = 0$$

$$P(X,Y,Z) = P_1X + P_2Y + P_3Z + P_4 = 0 \tag{3b}$$

We define an image plane with coordinates (x,z) parallel to the XZ plane a distance f in front of the eyepoint such that the Y axis pierces the coordinate axes origin. We also define the image x axis to be parallel to the eye coordinate X axis and the image z axis to be parallel to the eye coordinate Z axis (Fig. 5). Then the perspective transformation from eye coordinates to image coordinates can be represented as

$$X = kx$$
$$Y = kf \qquad (4)$$
$$Z = kz$$

where the parameter, k, relates to the distance from the eye, varying from a value of 0 at the eyepoint to a value of 1 at the image plane, and increasing along a ray from the eye out into the eye coordinate space.

Using Eq (1) through (4), we can produce a mathematically rigorous perspective transformation of any point (X_s, Y_s, Z_s) on a scene surface to a corresponding point (x,z) on the image plane. Furthermore, the parameter k provides a relative measure of distance from the eyepoint to all surface points which correspond to the same image point.

Of particular importance to the perspective validity of object geometry is the correct representation of surface boundaries. For an object in our scene data base, the boundaries include the silhouette curve of the quadric surface, the curves of intersection between the quadric surface and the bounding planes, and the lines of intersection between two bounding planes (Fig. 6).

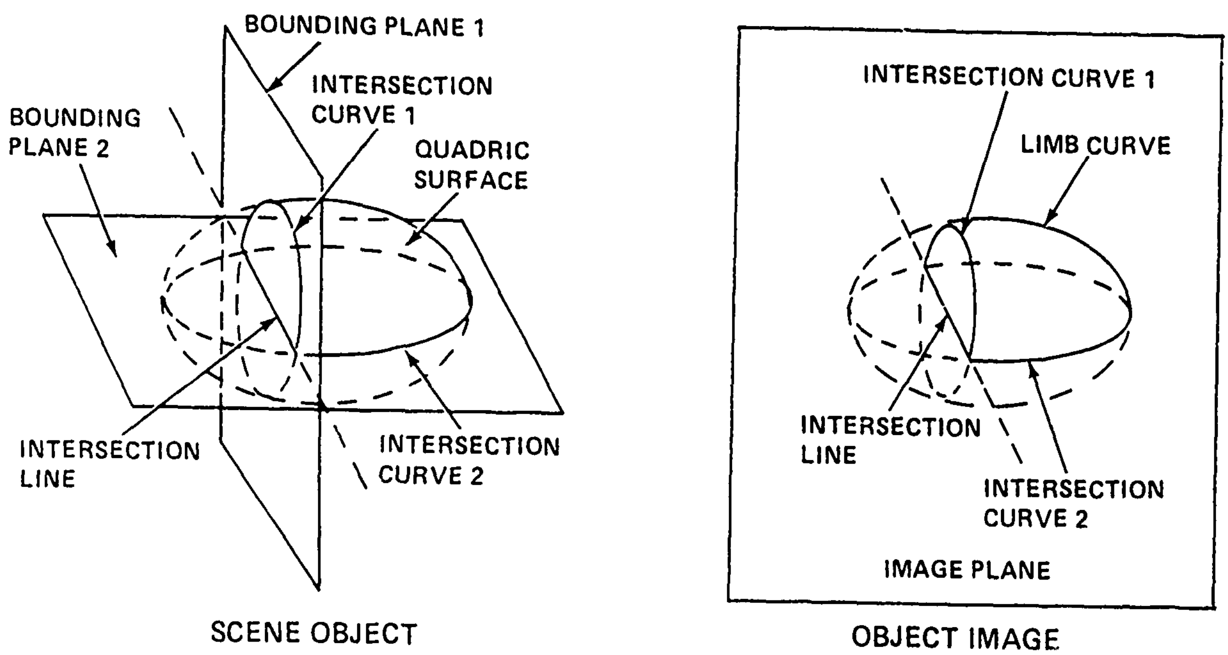

Figure 6 Perspective Projection of Object Surface Boundaries

The perspective projection of the silhouette curve of a quadric surface is called a limb curve and can be derived by substituting Eq (4) into Eq (3a) to obtain a quadratic equation in k,

$$Ak^2 + Bk + C = 0 \qquad (5)$$

where A,B, and C are expressions in the image coordinates x, z and f and in

the quadric surface coefficients. By definition, the limb curve is the set of image points for which rays from the eye are tangent to the quadaric surface. For these points k is single valued, so the discriminant of Eq (5) is zero.

$$B^2 - 4AC = 0 \tag{6}$$

This gives the limb curve as

$$f(x,z) = a_1 x^2 + a_2 z^2 + a_3 xz + a_4 x + a_5 z + a_6 = 0 \tag{7}$$

where the coefficients are expressions containing only the quadric surface coefficients and f, the distance from the eye point to the image plane.

The perspective projection of a curve of intersection between a quadric surface and a bounding plane can be derived by satisfying Eq (3a), (3b), and (4) simultaneously. Substituting Eq (4) into Eq (3b) we get

$$k = -P_4/(P_1 x + P_2 f + P_3 z) \tag{8}$$

Then substituting for k in Eq (4) and using the result in Eq (3a), we get the intersection curve image as

$$g(x,z) = e_1 x^2 + e_2 z^2 + e_3 xz + e_4 x + e_5 z + e_6 = 0 \tag{9}$$

where the coefficients are all expressions containing the quadric surface coefficients, the bounding plane coefficients, and f.

Similarly, the perspective projection of a line of intersection between two bounding planes can be derived by satisfying two equations of the form (3b) and (4) simultaneously. The result is

$$X_1 x + X_2 z + X_3 = 0 \tag{10}$$

where the coefficients are expressions containing the coefficients of the two bounding planes and f.

Equations (7), (9), and (10) give accurate representations of the images of all surface boundaries. To define object geometry in correct perspective we must remove all boundary segments that are occulted by object surfaces. This can be done by distance tests using the distance parameter, k, determined from Eq (5) and (8). We have developed efficient visibility logic using scan line coherence to perform this task, but a complete explanation of the procedure is beyond the scope of this paper.

Once all visible boundary segments are computed we have a valid perspective representation of object geometry. We also have an outline of each visible scene surface on the image plane. To determine object priority and surface shading, we can now examine image points within individual surface outlines and compute eye coordinates of surfaces which correspond to these image points. Again, Eq (5) and (8) can be used to determine relative distances and therefore surface priority. In addition, Eq (4), (3), (2), and (1) can be used to compute surface shading with perspective validity.

Surface Shading

To produce an accurate representation of surface shading we must include the effects of direct sun (or moon) illumination and atmospheric scattering, which produces an ambient illumination. These effects can be modeled mathematically using a defined scene illumination vector and the equations for scene surfaces which reflect the illumination. We can simplify the mathematics by transforming the illumination vector included in our scene model to eye coordinates using Eq (2). This will allow us to work in eye coordinates using Eq (3a) and (3b) for the object surfaces.

Surface shading due to reflected illumination has components due to diffuse reflection and specular reflection of the directional light source. In addition there is a component due to reflection of scattered, non-directional, or "ambient" light. Phong [4] has developed a mathematical model that has been widely accepted as a valid representation of these components. We base our model on Phong and express shading intensity as

$$I_R = (1 - a)\,[(1 - s)I_d + sI_s] + a \qquad (11)$$

where

- I_R = total reflected illumination intensity
- a = fraction of ambient illumination in the scene
- s = fraction of specular reflection for a given surface
- I_d = diffuse reflection intensity
- I_s = specular reflection intensity

The constants a and s are included in the scene data base. The constant a is a global constant specifying the percent of ambient illumination, and the constant s is a parameter included with each object defining the amount of shininess of the surface. The values I_d and I_s can be computed from the illumination vector, the eye vector and the equation of the reflecting surface (Fig. 7).

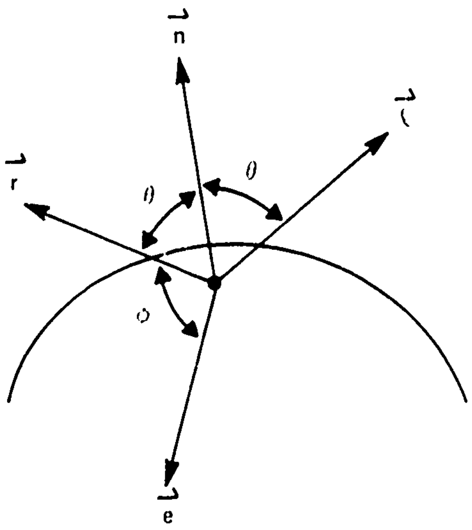

Figure 7 Geometry of Surface Reflection

$$I_d = \cos\theta = \vec{n} \cdot \vec{\ell} \tag{12}$$

$$I_s = \cos^m\phi = [\vec{e} \cdot \vec{r}]^m \tag{13}$$

where θ is the angle between the surface normal and the illumination vector and ϕ is the angle between the eye ray to the surface and the reflected ray. The constant m is a parameter included in the object data base to specify the degree of specularity that characterizes the surfaces of the object. The unit vectors $\vec{n}$, $\vec{\ell}$, $\vec{e}$, and $\vec{r}$ are the surface normal, illumination, eye ray, and reflection ray vectors, respectively.

It can be shown that

$$\vec{e}\ \vec{r} = 2(\vec{e}\cdot\vec{n})\ (\vec{n}\cdot\vec{\ell}) - (\vec{e}\cdot\vec{\ell}) \tag{14}$$

The vector $\vec{n}$ can be determined from Eq (3a) for quadric surfaces and from Eq (3b) for planar surfaces. The vector $\vec{e}$ is determined from the eye coordinates of the surface point being imaged.

In order to provide the high scene content necessary to represent real-world detail, we include optional texturing in our shading model. We assign each object in the scene a parameter, t, specifying what fraction of the overall shading intensity will be due to texturing. We extend the shading model to

$$I = (1 - a) \{ (1 - t) [(1 - s)I_d + sI_s] + tI_t \} + a \tag{15}$$

where I is the total shading intensity and I_t is the intensity of the texture applied.

To maintain perspective validity of the texture pattern, the pattern must be mapped onto surfaces in scene coordinates. We achieve this by generating texture patterns by means of a mathematical function of the scene coordinates,

$$I_t = F(X_s, Y_s, Z_s) \tag{16}$$

The scene coordinates are computed from the eye coordinates using Eq (2) in inverse form.

In summary, our CIG approach provides the control to generate images of curved and planar surfaces viewed from an arbitrary eyepoint and illuminated from an arbitrary direction with perspective validity of shading representing diffuse and specular reflection and textural detail.

Scene Environment

We have seen how a wide range of illumination sources can be modeled with CIG. Another importance element in perspective validity relating to scene environment is aerial perspective. Aerial perspective is produced by atmospheric scattering of light reflected from scene surfaces. Light reflected from distant objects must penetrate more atmospheric mass than light from close objects. A distant object therefore appears hazy because the eye perceives a combination of light reflected from both the object and the

atmosphere. CIG has modeled the physical phenomenology of aerial perspective very successfully using a weighted average of object color and atmospheric color. Using an exponential function of range as a weighting factor, the model attenuates surface shading and color with distance, blending the image intensity and color to that of the atmosphere.

Aerial perspective is a significant cue in depth perception over long ranges and is therefore essential to training missions involving navigation and target acquisition. Control of aerial perspective allows training scenarios to be performed under a wide range of environmental conditions. Lack of control of this valuable cue would minimize the training effectiveness achievable.

SUMMARY & CONCLUSIONS

Figures 8, 9, and 10 demonstrate how our CIG approach provides control of scene modeling and image generation necessary to maintain perspective validity in its three aspects.

Figure 8 shows a nap-of-the-earth approach to a target tank. The perspective validity of object geometry is demonstrated by the changing occultation of the tank and by the changing parallax between the trees. The perspective validity of surface shading is demonstrated by the consistency of sun shading and textural detail in all three views.

Figure 9 shows a CIG model of the Grumman X-29 aircraft flying among clouds. These images demonstrate how CIG can orient a moving target arbitrarily for each viewpoint to maintain perspective validity of object geometry. The images also demonstrate perspective validity of surface shading of curved surfaces. The reflectance parameters in the X-29 model include 25% specular and 75% diffuse shading.

Figure 10 shows two images of a rolling terrain scene viewed from the same viewpoint. The scene model for each of the two images contained different haze parameters to demonstrate the control of perspective validity of scene environment. Note how variations in aerial perspective affect depth cues.

Computer image generation provides the control necessary to maintain perspective validity of object geometry, surface shading, and scene environment throughout the wide range of mission scenarios demanded by military training. Unfortunately, this important capability has been overshadowed by the limitation in scene content achievable by current CIG systems. Consequently, it may seem advantageous to employ alternative technologies which provide high scene content at the expense of perspective validity. However, a thorough analysis of the cueing requirements for effective training will confirm the paramount importance of perspective validity. Continuing advances in computer hardware and image generation techniques will greatly increase the scene content attainable using CIG and CIG will produce this high scene content under complete control with full perspective validity.

Figure 8. Nap-of-the-Earth Sequence Demonstrating Perspective Validity of Object Geometry and Surface Shading

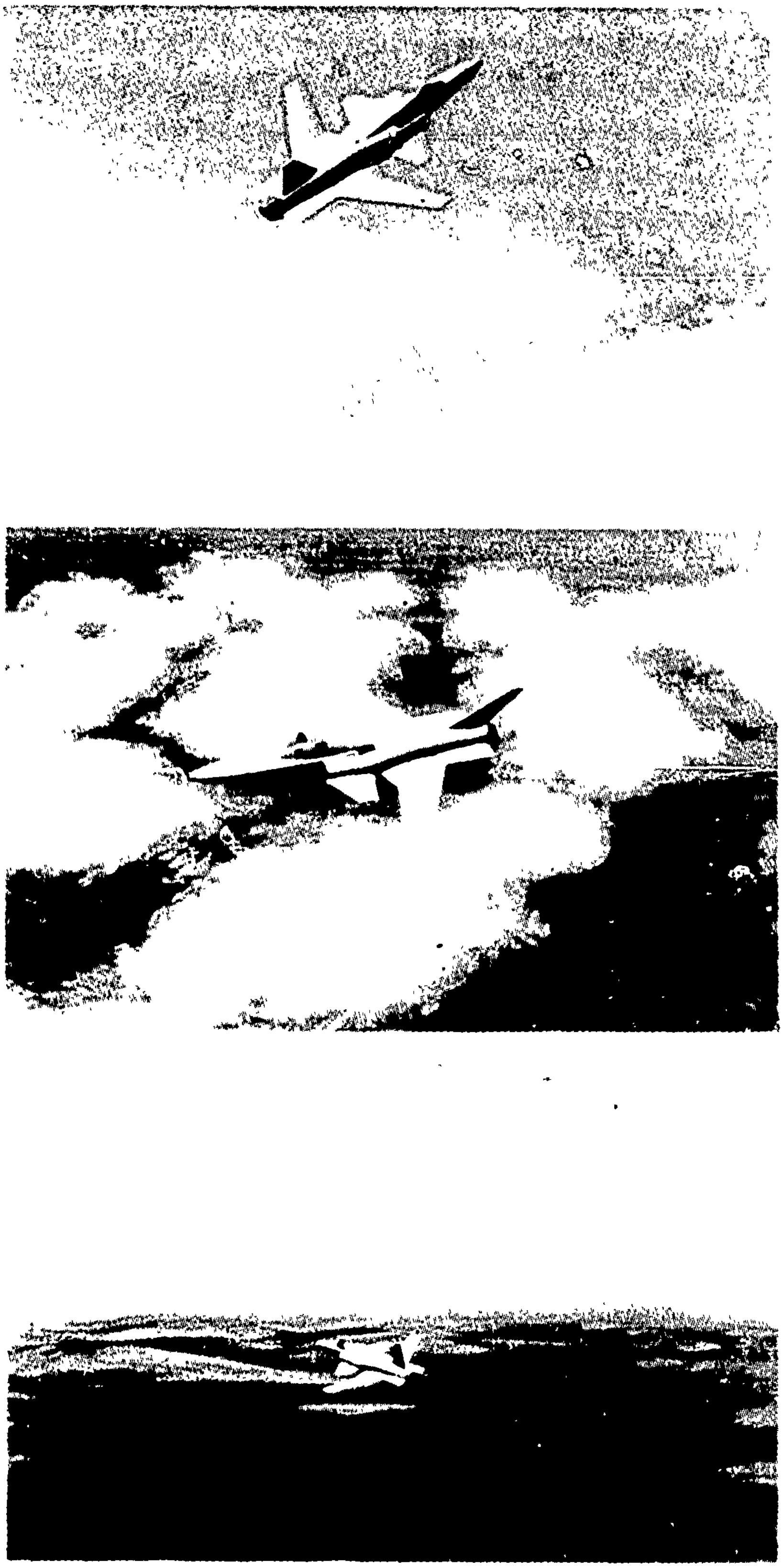

Figure 9. X-29 Aircraft in Clouds Demonstrating Perspective Validity of Object Geometry and Surface Shading

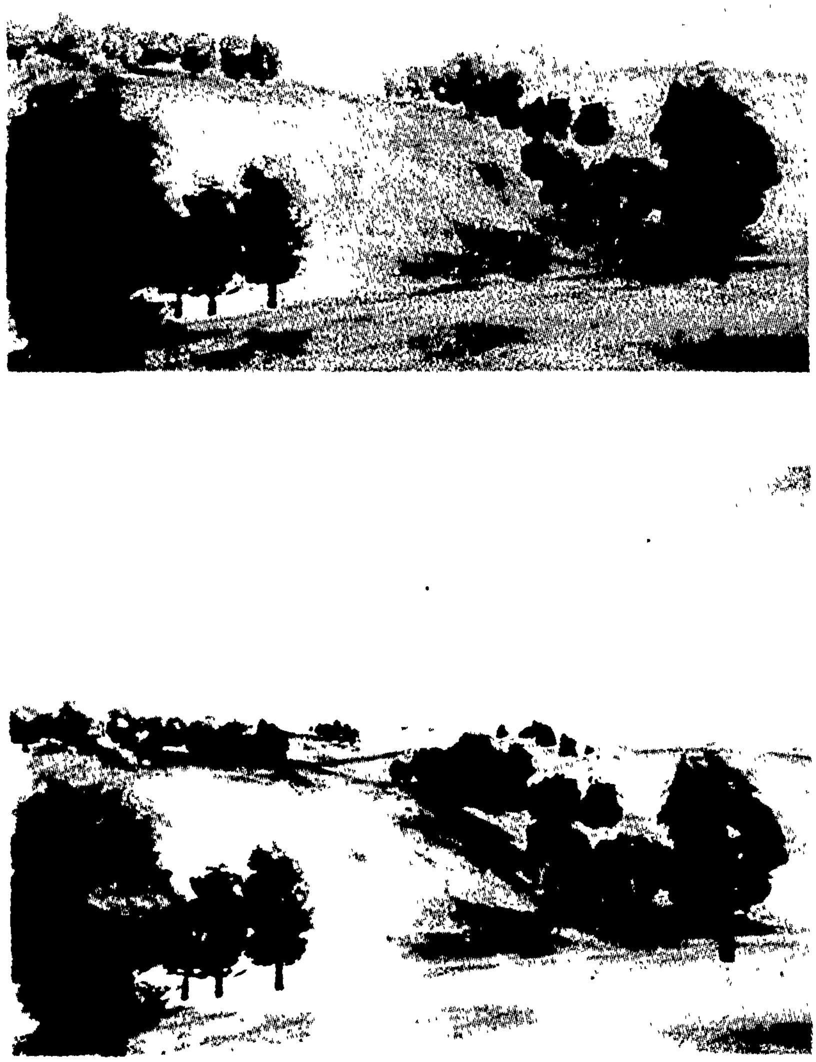

Figure 10. Rolling Terrain Scene with Different Examples of Aerial Perspective Demonstrating Perspective Validity of Scene Environment

ACKNOWLEDGEMENT

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COLOR VISUAL SIMULATION APPLICATIONS AT THE DEFENSE MAPPING AGENCY

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COLOR VISUAL SIMULATION APPLICATIONS AT THE DEFENSE MAPPING AGENCY

ABSTRACT

The Defense Mapping Agency (DMA) produces the Digital Landmass System data base to provide culture and terrain data in support of numerous aircraft simulators. In order to conduct data base and simulation quality control and requirements analysis, DMA has developed the Sensor Image Simulator which can rapidly generate visual and radar static scene digital simulations. The use of color in visual simulation allows the clear portrayal of both landcover and terrain data, whereas the initial black and white capabilities were restricted in this role and thus found limited use. Color visual simulation has many uses in analysis to help determine the applicability of current and prototype data structures to better meet user requirements. Color visual simulation is also significant in quality control since anomalies can be more easily detected in natural appearing forms of the data. The realism and efficiency possible with advanced processing and display technology, along with accurate data, make color visual simulation a highly effective medium in the presentation of geographic information. As a result, digital visual simulation is finding increased potential as a special purpose cartographic product. These applications are discussed and related simulation examples are presented.

INTRODUCTION

The Defense Mapping Agency (DMA) produces the Digital Landmass System (DLMS) data base to provide descriptive information on the earth's terrain and landcover for use in numerous aircraft simulators. DLMS was originally intended to support radar simulation, but due to its generalized form, it also contains information significant to visual simulation. To help determine the applicability of DLMS to visual simulation, DMA developed an initial sensor simulation capability which confirmed that DLMS could produce very accurate visual and radar simulations. The initial capability evolved into the Sensor Image Simulator (SIS) which was installed at DMA in 1981. The SIS can rapidly generate realistic radar and visual static scene simulations providing operator control over all characteristics of the simulation. In addition, extensive interactive edit capabilities allow changes to be made to the data base. The use of color has further expanded the capabilities of visual simulation by allowing the clear portrayal of both landcover and terrain.

As a result of studies conducted on the SIS, a number of advantages and disadvantages have been observed in various data bases contributing to DMA's awareness for data base requirements. In addition, during the generation of simulations, anomalies have been discovered in the data which could not be detected in the more basic off-line, or original digital form of the data. This has made it evident that the visual simulation can also play a significant role in the quality assurance of data production. It also has become clear that the realistic scenes which can be generated make excellent perspective maps, introducing the potential for visual simulation as a cartographic product for special purposes when perspective views are helpful.

In DLMS, terrain is represented by Digital Terrain Elevation Data (DTED) in which terrain elevations are recorded at three second intervals in latitude and

and longitude. Landcover information consists of man-made and natural features which are defined by points, lines and areal boundaries with associated descriptors forming Digital Feature Analysis Data (DFAD). Each data type is produced in geographic rectangular cells varying in size, but usually consisting of one degree of latitude by one degree of longitude. The data set and actual DLMS data is DISTRIBUTION LIMITED releasable only to DoD components and those contractors with a valid DoD contract.

THE SIGNIFICANCE OF COLOR

Color is a key factor in providing realism to visual simulation. The use of color allows the easy identification of features and provides a natural appearance to the scene which enhances its acceptability. In addition to these obvious benefits, the characteristics of color make it particularly suitable to the analysis and use of DLMS.

Color can be perceptually defined in three dimensional space by intensity, hue and saturation (IHS) attributes. This has been described in the C.I.E. (Commission Internationale de L 'Eclairage) chromaticity diagram and can be approximately represented in a cylindrical coordinate system. Using this system, a color can be created from the three dimensional cylindrical coordinates through a mathematical transformation to the color producing system of a display device.

The DTED and DFAD components of DLMS can be considered as forming a two dimensional data structure, each of which can be represented by a dimension of color. The DFAD is used to determine the hue of a picture element, while DTED, through slope shading, determines the intensity. The result, when using conventional hues, is a natural appearing color simulation. Of at least equal importance to the appearance of the image is the fact that each of the two DLMS components are revealed as separate attributes in the same image through the hue and intensity dimensions of color. This allows the simultaneous viewing of two related, but separate, data bases with the ability to distinguish between them. Color provides the clear portrayal of both landcover and terrain data to help determine DTED and DFAD compatibility as a quality assurance check. Color has added considerably to the usefulness of visual simulation at DMA over the initial black and white capability which, although impressive, found limited applications by being essentially confined to the portrayal of terrain.

Figure 1. is a simulation looking towards Mt. Rainier in flight above Tacoma, Washington. In the color image, hue makes it easy to identify soil, trees, residential buildings, commercial buildings, water, snow and rock, while intensity helps to depict the terrain characteristics in the mountains.

Saturation may be used to create atmospheric effects such as haze or fog. Diluting colors with white causes them to become unsaturated, closely simulating the effect when sunlight is reflected from water vapor in the viewer's line of sight. This is significant in indicating to the simulation user the possible visibility conditions as opposed to the theoretical scene based solely on culture and terrain data. Figure 2. shows the effects of atmospheric haze while looking towards Mt. Rainier from above Ft. Lewis, Washington. Note that in this particular situation, visibility decreases with range, but increases again in the higher elevation mountains.

DATA BASE APPLICATIONS AND REQUIREMENTS

DMA is continuously striving for improvements to the Digital Landmass System data base to better meet user requirements for suitable and accurate data. The visual simulation capability on the SIS system allows DMA to perform requirements analysis studies to help determine the applicability of current and prototype data bases to visual simulation.

One of the major problems in defining the specifications for a standardized data base applicable to all systems is the fact that every simulator system may have individual data base requirements. The SIS at DMA uses just one technique out of many for visual simulation and is not necessarily representative of the capabilities, or methods, of user systems for which DLMS is primarily intended. As a result, data base requirements are based largely on the research of current and potential users of DLMS data. The application studies conducted at DMA are useful in complementing user research by providing additional work, detecting results which may not be observed on some user systems, and through the flexibility of the SIS, may provide experimentation not possible by the user. In addition, the visual simulation capability helps DMA to better understand data base requirements and problems from the user's perspective.

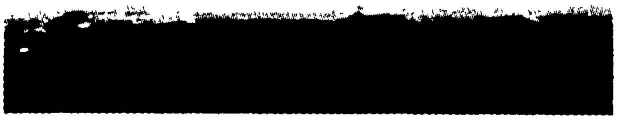
The Sensor Image Simulator uses off-line DTED and DFAD data in a DLMS product specification format. The data is then directly transformed to an on-line data base to which necessary corrections may be made. Since the SIS is a static scene system, it is relieved of real time constraints such as the stylized representation of terrain using large polygons or compression of feature information. This allows the creation of highly realistic scenes displaying all of the original DTED and DFAD. The success or failure of a scene accurately simulating the real world is then a direct reflection of the data base. If a simulation falls short of providing an accurate representation, then the scene, in conjunction with interactive query and edit capabilities can be used to determine what information is missing. On the other hand, if a simulation is successful, then it is possible to determine why, including what features were significant and how they contributed to the scene. The edit capabilities can be used to provide a complete description of a selected location revealing its off-line characteristics.

Figure 3. is a simulation of Mt. Rainier and Figure 4. is an actual photograph taken from nearby Crystal Mountain. This comparison demonstrates the accuracy of the simulation and indicates that most of the significant information is in the data base. Note however, that the river in the actual photograph, which helps define the valley floor, is missing from the DLMS data. In this case, the river was not included in the data base because it did not meet previous specifications for portrayal. A new product specification was designed to portray this feature, as well as roads, road interchanges, railroads and right-of-ways. These changes were made in response to user requests and were supported by SIS studies conducted at DMA.

Figure 5. is a simulation looking east over Seattle, Washington using DLMS data which has an approximate ground resolution of 500 ft. This data appears generally adequate for long range visual simulations. Note in Figure 6. the additional character portrayed in the city using DLMS Level 2 DFAD data. Level 2 data has an improved ground resolution for shorter range simulation, but is more expensive to produce and greatly increases the amount of data to be processed in the simulation.

Figure 1.

Figure 2.



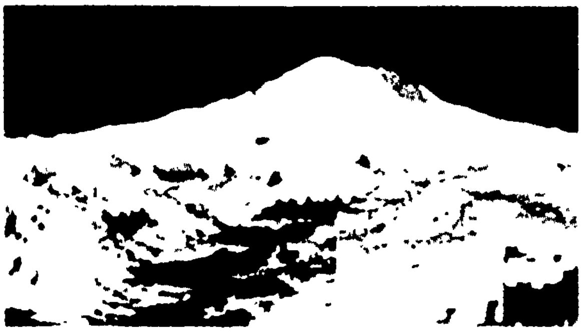


Figure 3.

Figure 4.

Figure 5.

Figure 6.

One of the requirements which may be necessary in a visual simulation data base is features which can be used to allow the generation of useful colors significant to color visual realism. Such features are sometimes not essential to radar simulation and thus may not be included in the data base. In a visual simulation over mountainous terrain, a feature portraying rock above timberline may be very useful in creating a rock or snow color, as opposed to the same soil or grassland color used in the valleys. Most of the mountains in Colorado, for example, use the same soil feature for both the mountain tops and valleys, making it impossible to create separate colors without the addition of new features to the DLMS data. The appearance of Mt. Rainier, in Figure 3., is enhanced by the use of a snow feature.

In addition to visual out-of-window simulations, DMA is developing electro-optical sensor simulations, such as forward looking infra-red, in an effort to keep pace with potential applications of DMA data bases.

QUALITY ASSURANCE

One of the principal concerns of DMA is the quality assurance of the products it produces. This is a formidable problem for the Digital Landmass System data base due to the vast amount of data produced and the abstract characteristic of its most basic form as numeric quantities and relationships. Although the data represents the natural landforms, which can be easily comprehended, the off-line format of the data involved in the production, processing and storage at DMA is often not directly observable in the natural conditions it is designed to represent. As a result, it is sometimes difficult to detect some types of errors which may appear in the data.

Most potential errors in the DLMS data can be eliminated during production phases through the use of various automated and manual quality control checks. Some anomalies, however, remain transparent to these techniques without the transformation of the off-line data to a natural appearing form through the use of visual simulations and related advanced on-line data base displays. Errors can be more easily detected when the maximum contrast can be created between the two conditions of the familiar form of the landscape and the unnatural situation generated by an anomaly. Thus, the more natural the data can appear, the easier it is to observe an error in the data.

Figure 7. is a display of the off-line DFAD near Seattle, Washington. Although a major error exists in this data, it is virtually impossible to detect it using the information directly available from the off-line format. Using a visual simulation of the same area in Figure 8., it can be seen that most of Bainbridge Island is missing. The on-line data base used to generate the visual simulation is seen in Figure 9. In this orthogonal view, the illumination of the terrain was increased to reveal that although the island exists in the DTED, it is largely missing from the DFAD. This problem was caused by a small coding error in the DFAD, which had fatal results on the data. In addition to the importance of generating good images, the SIS has the capability to interactively interrogate and edit the data to correct discrepancies and offload the corrected data for insertion to the DLMS data base.

Perhaps the largest problem facing the quality assurance task is the large volume of the data produced by DMA. For example, a single production cell of DFAD covers about two thousand square nautical miles and contains approximately two thousand features. Almost one half million features are produced each year. Each feature is defined by ten descriptive codes and consists of from one to eight thousand coordinates. A single error in this data set may cause an anomaly to exist in a simulation scene. Likewise, a single one degree square cell of DTED contains almost one and a half million elevation points susceptible to potential errors. Visual simulation is very effective in displaying these vast quantities of information in a single, natural presentation.

As mentioned earlier, color visual simulation is useful in checking the coherence between DTED and DFAD. These two components of DLMS are registered to each other by virtue of their individual positional accuracy specifications. This is usually sufficient for simulation. The biggest problem concerning the compatibility of DTED and DFAD is observed in visual simulation when features in DFAD fail to assume their correct position on the terrain, such as when water in DFAD extends beyond shorelines onto hillsides defined from DTED. Visual simulation is also useful in helping to determine the continuity between the individually produced geographic cells which are mosaicked together to create the DTED and DFAD data bases.

The use of color is critical in determining feature analysis data classes. In the quality assurance role, the choice of colors is best dictated by their effectiveness for identification, although some convention adds to the important natural appearance of the data.

Although visual simulation can be a very effective tool in providing quality assurance, it also has a number of limitations. Hidden surfaces and the decrease in the amount of observable information as a function of range are examples of such drawbacks. Therefore, visual simulation cannot replace traditional techniques, but it can effectively complement them to provide additional control.

APPLICATIONS IN CARTOGRAPHY

One of the principal purposes of cartography is to effectively communicate geographic information using a graphic medium. The era of digital cartography has greatly expanded the range of capabilities for cartographic communication by allowing the rapid manipulation of data into graphics best suited for an intended purpose. The realism and efficiency possible with advanced processing and display technology, along with accurate data, have made it possible to produce highly realistic graphics using perspective views. The perspective view is particularly significant in creating a natural presentation allowing the user to more closely associate geographic data with the real world. Perspective views are not new, but the fast generation speeds and flexibility which can be realized through digital visual simulation have provided a new capability to cartography. As a result, visual simulation is finding increased potential as a cartographic product for applications where the advantages of perspective views are useful.

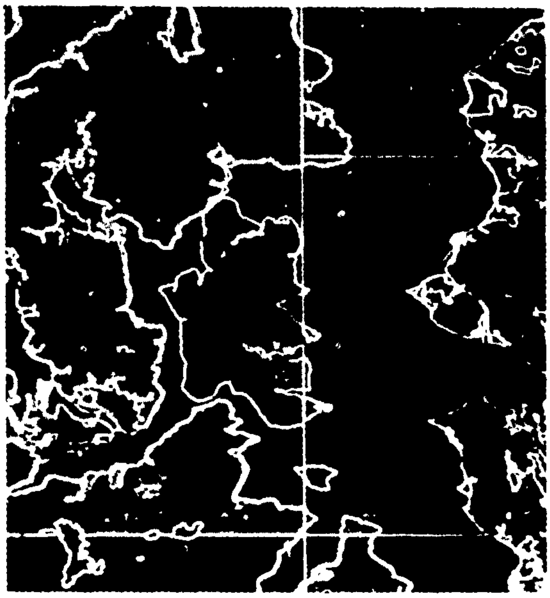


Figure 7.

Figure 8.

Figure 9.

Speed is a significant factor in the success of visual simulation applications to cartography by allowing the observer to rapidly regenerate scenes to obtain improved views, maximizing the potential value of the data. Real time speeds can also introduce the added dimension of time to the data presentation.

The vast amount of descriptive information available in digital data bases makes it possible to select specific attributes for display, creating thematic simulations. Furthermore, different attributes, such as basic surface materials or calculated radar reflectivity potential, can be changed and the scene quickly regenerated to display a new thematic category. Figure 10. is an example of a thematic simulation showing potential radar reflectivity based on DLMS DFAD descriptors. Radar reflectivity is indicated by a spectrum of hues such that red is the highest reflectance and blue is the lowest.

The ability to manipulate the visual simulation to improve its presentation is very useful. One of the problems with perspective views is the difficulty in displaying terrain information due to the small ratio between surface elevations and horizontal distances usually found in nature. Vertical exaggeration is useful to overcome this problem. The simulation in Figure 11. is a normal simulation of Mt. Rainier looking towards the north. Figure 12. is the same except it has been vertically exaggerated by a factor of two. In this case, vertical exaggeration has grossly misrepresented the vertical dimension of the terrain, indicating the effects possible in areas of high relief. The same exaggeration factor applied to an area of low relief would retain the general characteristic of the terrain.

The effect of the earth's curvature can be an improtant factor in accurate visual simulation. Figure 13. is a simulation with earth curvature looking north, 60 miles from Mt. Rainier, at an altitude of 15,000 feet. Figure 14. is the same simulation without earth curvature. Although the differences are slight, they do exist.

The use of aerial photography in place of a digital culture data base can produce actual perspective views. Figure 15. is a simulation using LANDSAT Thematic Mapper data natural color bands of Blytheville Air Force Base in Arkansas in conjunction with DMA DTED. This type of simulation can be particularly significant due to its realism, but requires very large digital aerial photography data storage relative to DLMS DFAD storage. In addition, atmospheric and sunlight effects, as well as geometric constraints, limit the flexibility of using aerial photography.

It is generally not feasible to produce visual simulations as a standard cartographic product since the viewer's perspective is often unique to a specific application. For special purposes, however, ranging from battlefield maps to strategic planning briefings, digital visual simulation is becoming increasingly significant.

CONCLUSION

The visual simulation capability at DMA has proven very valuable and will be continuously improved to meet new requirements. The growth of visual

Figure 10.

Figure 11.

Figure 12.

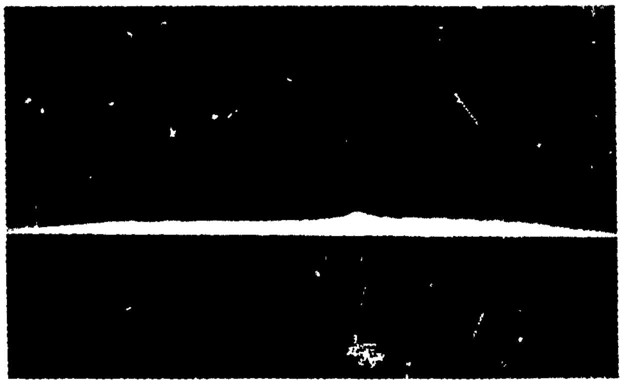


Figure 13.

Figure 14.

Figure 15.

simulation applications for training purposes and cartographic products will place an increased demand on DMA data base requirements and production. To help meet this challenge, visual simulations at DMA will continue to serve requirements analysis, quality assurance and special products.

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AUTOMATED AND INTERACTIVE DATA BASE GENERATION

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ABSTRACT

Until the mid 70's, visual simulation had been limited to small areas - primarily airfields and aircraft carriers - and complexity of the data bases was quite restricted due to the limited capacity of the image generators.

Today training simulators require realistic terrain and gaming areas encompassing hundreds of thousands of miles, yet need accurate highly detailed "insets" for nap-of-the-earth flights. This paper will discuss improvements in data base generation technology which have allowed gaming area realism to keep pace with rapid advancement of Image Generator capabilities.

INTRODUCTION

In the late 70's, a radical change in requirements and structure of CIG data bases occurred which had a lasting affect on the data base creation process. Up to that time, data bases were comprised of three dimensional models located on a flat default ground plane and covered a very limited area-usually an airfield. In that era, modeling was done by hand and was treated quite casually - almost as an afterthought. The requirement for wide area data bases suitable for low level navigation necessitated an automatic generation technique and a new rolling terrain data base structure. In this structure, the gaming area is covered with a continuous blanket of terrain faces which may have coplanar "culture" such as roads, fields and lakes. Three dimensional models are then placed on top of rolling terrain. Contract requirements often specify a real world gaming area to correlate with navigational equipment so the concept of generic data bases cannot be used.

The data base modeling system offers great flexibility in modeling techniques, ranging from totally automatic to interactive to totally manual. This paper discusses how GE responded to the new CIG data base requirements in terms of automation, interactive modeling tools and visual aids.

AUTOMATED PROCESSING

In 19 6, GE received a contract for a prototype B52 simulator to be used for cross country training missions. The required data base of 250,000 square miles could be economically generated only by an automated technique. Input would be obtained from DMA terrain and culture manuscripts in digital form and processed in CIG data bases using algorithms controlled to some extent by user established parameters. The result was to implement a batch processing approach with a minimum of human intervention. Only inexperienced clerical help was required to monitor processing (mounting tapes, handling line printer output, and noting error messages).

On the C-130 program, the transformation program, was further refined. A series of batches (a 12 arcminute x 12 arcminute area constitutes a batch) can be strung together and processed overnight with no human intervention. In areas of sparse culture, data up to nine batches, or 36' x 36', can be run overnight. Although the transformation is a batch-oriented process, predefined embedded control parameters allow a great deal of flexibility in tailoring the automated processing output. These parameters are defined in a process control file, which can be altered for different image generators or tailored to match gaming areas with specific training requirements.

Processing is segmented into three steps - terrain derivation, culture derivation and merging of terrain and culture.

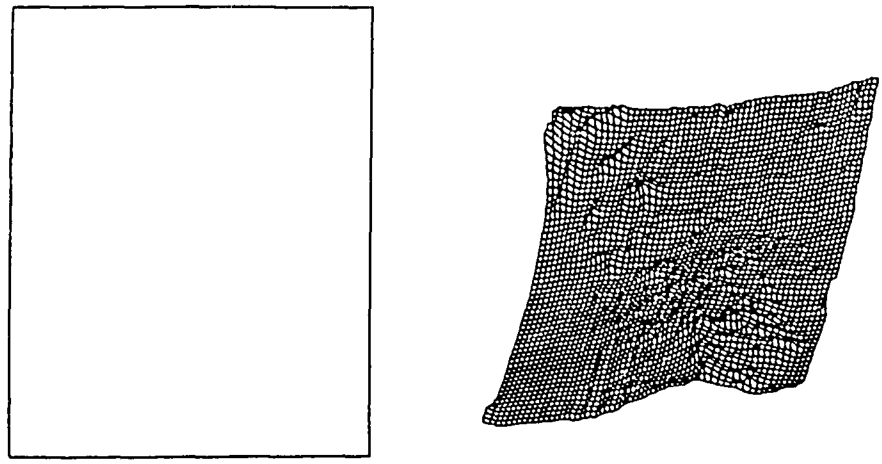
1. TERRAIN DERIVATION

DMA terrain manuscripts are comprised of elevation grid points whose sampling interval is a function of latitude. For example, below 50 degrees latitude the sampling interval is 3 arcseconds, or about 300 feet. The task of the transformation is to derive a network of terrain triangles approximating this elevation grid. The user selects a grid spacing suitable to the density of the data base to be produced. A terrain network is then formed from selected DMA elevation grid points which become vertices of the terrain triangles. Vertex selection is based on two criteria: 1) points with the greatest curvature, and 2) points which preserve a fairly regular terrain network.

The first criterion is obviously intended to preserve significant peaks, valleys and ridges. The second criterion is intended to distribute the scene content fairly evenly over the gaming area to avoid extreme fluctuations in CIG processing load. The relative importance of the criteria is a user parameter which trades off "goodness of fit" for regularity or vice versa.

The next step is the application of a filter to the terrain elevation data to detect significant contour inflection points representing peaks and valleys. The filtering process takes into consideration the elevation of neighboring points, where closer proximity points carry a greater weight than more distant points. Figure 1 shows a plot of points with high positive curvature and a "fishnet" plot of DMA source data of the same region. As you can see, the filter does a good job of detecting peaks and ridges.

The transformation generates seven versions of the terrain. The coarsest approximation (level of detail 7) is comprised of 64 triangles for a 12' x 12' region with each succeeding version containing twice as many. Thus,



High-Curvature Points

Plot of DMA Data

Figure 1

the finest terrain representation (level of detail 1) contains 4096 terrain triangles for the same 12' x 12' region. GE has made varying use of the seven terrain versions or LOD's on different simulators. B52 used only the LOD 4 version containing about 4 terrain faces per square nautical mile (nm2). C-130 uses a replacement scheme where the horizon is formed by LOD 7 terrain with transitions to successively finer versions ending with LOD 3, containing about 8 terrain faces per nm2. AVTS uses two versions of the terrain, 1) the LOD 3 version is used for fine terrain active to about 8 miles, and 2) with LOD 6 used for coarse terrain active to about 17 miles, although both higher and lower density options are available.

Besides forming the triangles, terrain processing performs two other important functions - clustering and blocking. Adjacent terrain triangles are grouped into clusters which are used by the IG for three purposes: 1) for the culling (channel assignment) process, 2) for level of detail selection, and 3) for priority ordering of terrain faces. The level of detail usage implies that a linkage must be established between clusters at one LOD and clusters at both the next coarser and next finer LOD's. In the C130 CIG this allows a scene to include terrain at many LOD's simultaneously where each cluster's LOD is a function of distance from eyepoint and projected size on the display. AVTS and VSCDP do not use this replacement LOD terrain concept. The terrain clusters are grouped into geographic blocks for two IG functions, 1) for a first step in the culling

process, and 2) for the dynamic update on the IG environment memory. Each block, or geographic area, is assigned the proper latitude and longitude so the real time system can transfer the appropriate portions of the data base from disc storage to on-line environment memory based on proximity to the eyepoint.

Terrain processing, excluding the initial transfer of DMA source tapes to disc, requires about 25 minutes on a Perkin Elmer 3230 computer to generate seven versions of the terrain for a 12' x 12' region. The time can be reduced to about 10 minutes if LOD's 2 and 1 are not generated.

2. CULTURE DERIVATION

In this discussion culture processing refers to the automated selection and generation of CIG usable data from DMA culture manuscripts. Until recently IGs have used Level I and Level II manuscripts, but software modifications have been made to accept the more detailed Level V data.

The first step is to certify the validity of the culture manuscripts and to transfer them from tape into disc. Checks are made for two error categories - invalid codes and invalid shapes. The tape-to-disc process is called culture blocking because it stores the data in geographic blocks, slicing features on block boundaries. Culture features frequently contain far more vertices than are required to produce a good visual display. Since one of the primary culture processing functions is reduction of data to a manageable quantity for the CIG, the "excess" vertices are eliminated during culture blocking. A digital filter is applied to both polygonal and lineal features to eliminate some vertices while maintaining the feature's shape, orientation and position. The filter attempts to select the minimum number of vertices such that all original vertices are within specified distance of the edges in the simplified feature. Figure 2 illustrates the vertex selection algorithm.

Vertex selection continues until the specified minimum distance is reached. This parameter is user controlled. It was set at 25 feet for C-130 and 10 feet for AVTS.

CIG's process faces or polygons but not lineal features (i.e., straight line segments). The culture blocking function provides a "path" function to create polygons (called areal features by DMA) from lineal source features. Thus a road or railroad defined by a series of turn points in the DMA source data is expanded into a string of connected polygons with user selected width.

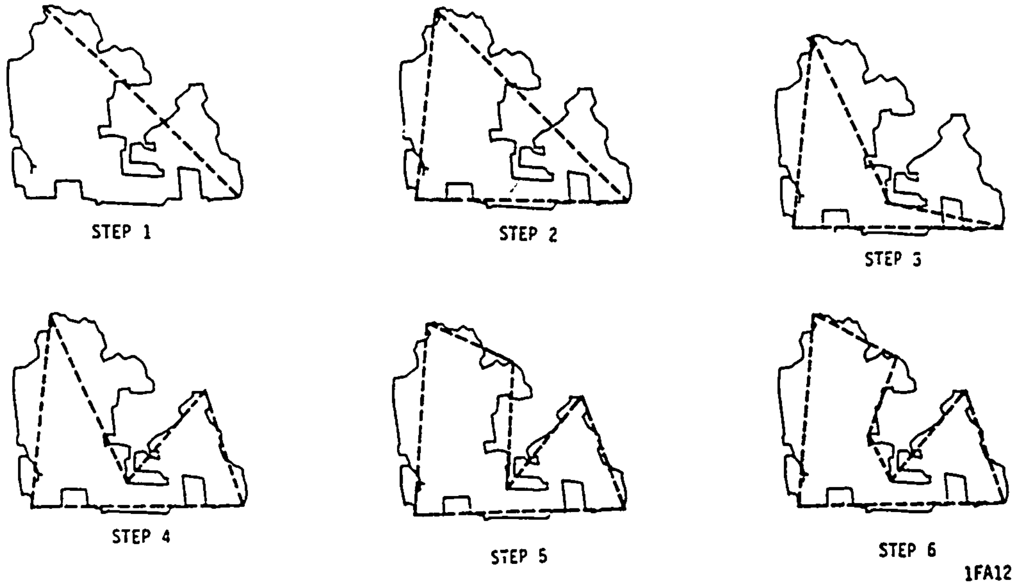


Figure 2

The primary attributes for CIG faces are color and texture, neither of which is included in DMA culture manuscripts. Color and texture codes are assigned during culture processing under the control of user supplied parameters which assign them based on feature type. The user may also introduce models from the model library into the data base by associating them with DMA point features such as radio towers and power pylons. Note that this controls model location but not the model definition itself.

Another significant culture processing function is level of detail (LOD) control. LOD is performed by the CIG by either making more features active near the eyepoint than in the distance (called "delta LOD" because each LOD is an addition to all coarser LOD's) or by replacing coarse feature versions with more detailed versions (replacement LOD). The transformation supports both types of LOD. For delta LOD it determines the LOD cutoff based on area for areal features. Thus, only large features will be propogated into coarse LODs and hence displayed in the distance. To support replacement LOD the transformation generates four versions of each feature, where each successively coarser version contains 60% as many edges as the previous version. Figure 3 illustrates four versions of a river derived using this algorithm.

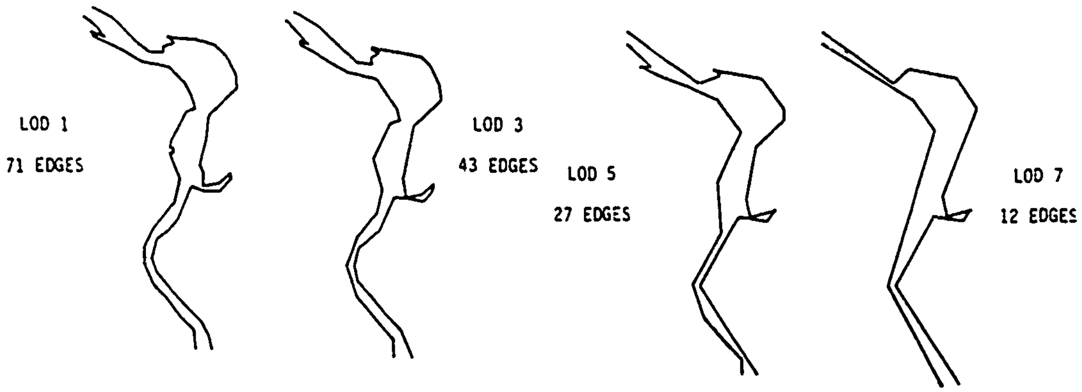


Figure 3

3. TERRAIN AND CULTURE MERGING

Up to this point terrain and culture are processed independently. Some very important functions requiring reference to both terrain and culture are performed during their merging.

The terrain representation has no color or texture since it was derived only from elevation data. On the other hand, the culture representation has no elevations since it was derived from latitude, longitude data.

During the merging process, the missing color, texture and elevation attributes in each set of data are extracted. Where no culture feature exists, a default "normal soil" color, an input parameter, is assigned.

Each CIG face must be planar and convex. Therefore, before assigning elevation, the surface culture must be fragmented to conform to terrain boundaries, and then possibly refragmented into convex faces. The elevation of each culture vertex is then computed from the underlying terrain. Figure 4A and Figure 4B show examples of fragmentation.

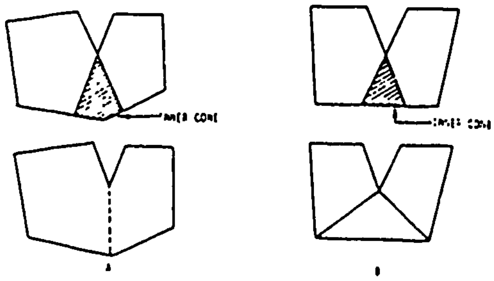


Figure 4

The fragmentation process may introduce inefficiencies into the data base - instances where extra edges and faces were created that contribute little to the scene. A "cleanup" is performed which eliminates inefficiencies such as the two cases illustrated in Figure 5. Further cleanup is performed by the CIG itself via the small face blend and discard mechanism.

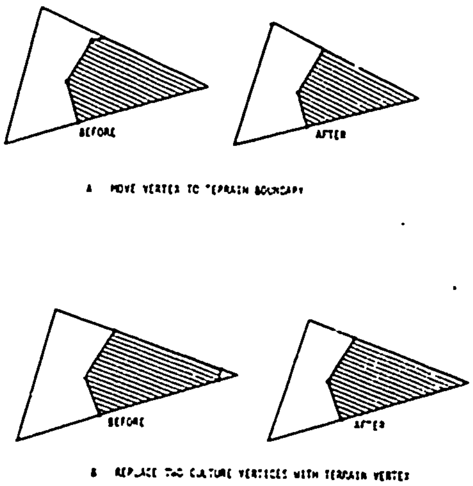


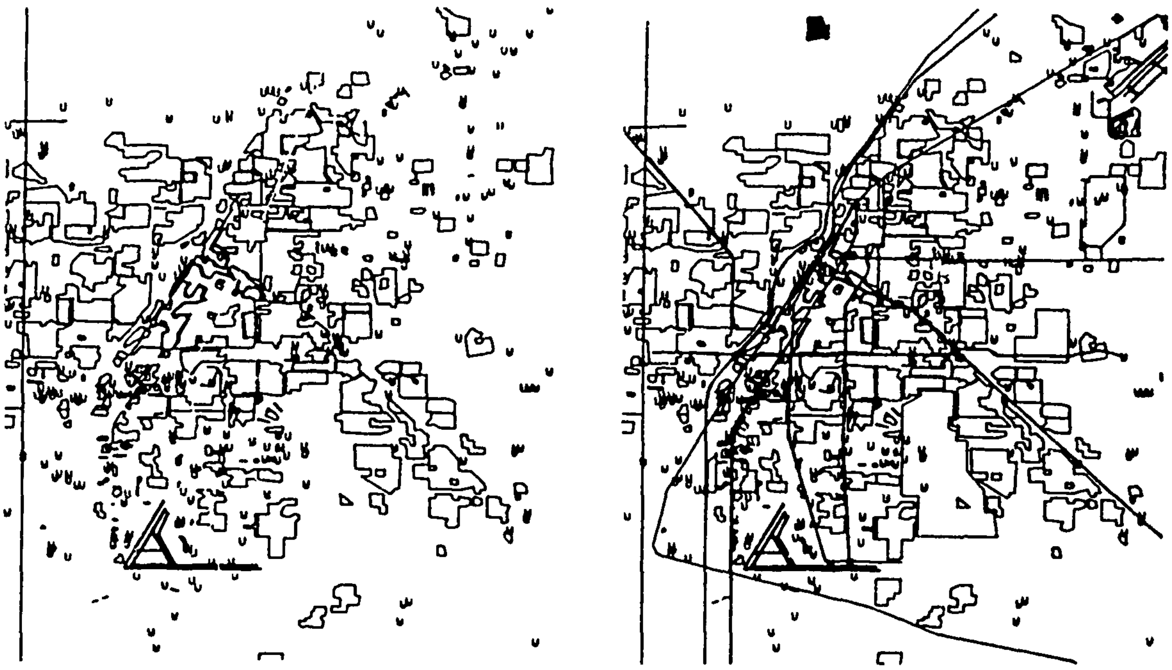
Figure 5

Not until the above steps are completed can the data base density be assessed. The user can establish limits for each geographic area and each LOD. When the limit is reached, the excess data can be discarded or stored in the next finer LOD. To cope with this data overflow condition, the user assigns a feature importance code to each feature type so the ones discarded will be those that he views as the most expendable.

INTERACTIVE PROCESSING

Automated processing can produce large data bases in a very efficient manner, but interactive enhancement may still be needed to improve specific areas or to overcome DMA data limitations. To accomplish this, GE developed a set of interactive software tools to facilitate the data capture process and the modification of existing data. The culture digitization and modification tool (called interactive culture) has proven to be a highly flexible and efficient modeling tool. In a recent digitizing session, all the major rural highways in the AVTS gaming area (10,000 nm2) were digitized in 4 hours. This kind of productivity is allowing GE to continually improve the quality of delivered data bases.

The user interface consists of a high resolution 14" calligraphic (line drawing) display with a crosshair cursor and alphanumeric terminal and a 30" x 40" digitizing tablet with a crosshair puck. Thus two methods of data entry are available. When correcting existing data or adding features in locations relative to existing data the display cursor is used. When adding data from maps or drawings the digitizing tablet puck is used. Figure 6 shows the Las Vegas area culture from DMA level I and the same area after enhancement by GE using the interactive culture tool.



Raw DMA Data

Enhanced DMA Data

Figure 6

Map registration and display window definition are independent functions. This allows the user to view the digitizing process at close range when a high degree of precision is required, even when digitizing from a large scale map. Display setups can be easily saved and recalled, facilitating switching between "big picture" and zoomed displays or between different areas of interest.

Normally the digitizing process begins by defining the area of interest and loading the DMA culture data for that area into a scratch file which is used for subsequent displays and to accumulate digitized data. Optionally the user may recall a scratch file from a previous digitizing session or he may initialize an empty file. Further flexibility is offered through selective save and restore. Thus a user can work with a subset of all data, such as only roads or only data that he digitized. This can result in considerable savings in replotting time.

There are several digitizing modes which enable the user to digitize all CIG feature types. In areal mode, closed polygons are digitized resulting in surface features. In path mode, turn

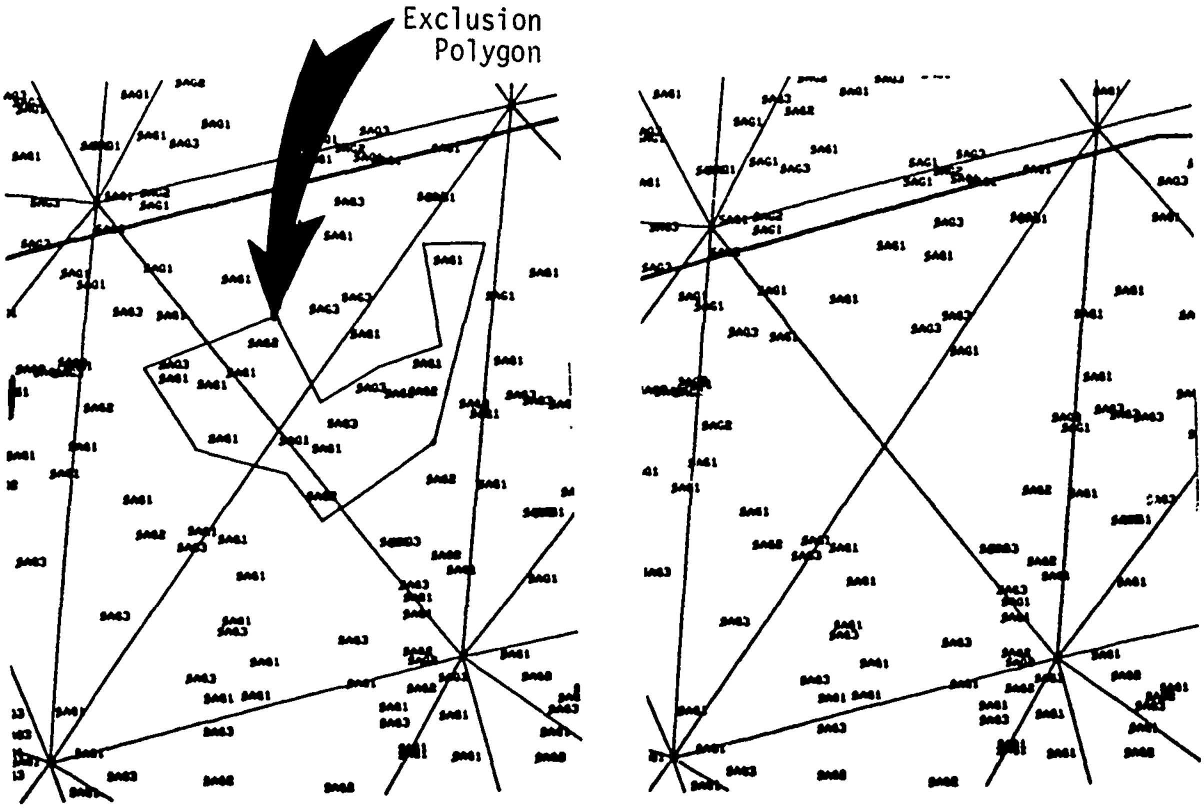
points are digitized which are expanded into surface polygons by the software. In point light mode the start and end points of a point light string are digitized and the number of lights in the string is entered, with spacing computed by the software. In model mode, locations of individual models or universal features are digitized. In vertex mode, a vertex of an existing feature can be added, deleted, or moved. The correction capability is very important when data from multiple sources is being combined into the same data base. Discrepancies between data sources can result in discontinuities between features, for instance a road may not meet a bridge or a river may not connect to a lake. These situations can be corrected by visual inspection and vertex adjustment.

Selection of feature(s) to be modified - called "lockon" is - normally done visually by positioning the cursor on the feature. However, in many instances it is desirable to lock onto all features having certain attributes - for example to change the color of all lakes, or to delete all industrial areas, or to plot all highways. A search function allows the user to define his selection criteria and initiate the search, locking onto all features meeting the criteria. The following command will then apply to this list of features until they are "unlocked".

Recent systems including AVTS and VSCDP have a universal feature capability, an on-line model library used to create 3D texture or ground clutter throughout the gaming area. Explicit placement of each rock, bush and tree would be an overwhelming burden on the modeler. The AVTS data base includes approximately 1.6 million EUFs in 10000 nm2. Therefore, a controlled random scatter function has been provided as an interactive tool. Using this technique the user digitizes a scatter polygon defining the boundaries within which the scatter will apply. He then defines the universal feature and scatter density and the random scatter is performed automatically. More than one feature type can be scattered in the same polygon. Another approach to scattering is sometimes more appropriate. An option is imbedded in the batch processing to scatter over the whole area. Then using the interactive tool an exclusion polygon can be digitized and universal features within that polygon are automatically deleted. This approach is being used in the AVTS Nevada data base to remove vegetation from dry lakes. Figure 7 illustrates these two approaches.

In another mode, individual EUF's can be quickly added or deleted by placing the cursor at the desired location.

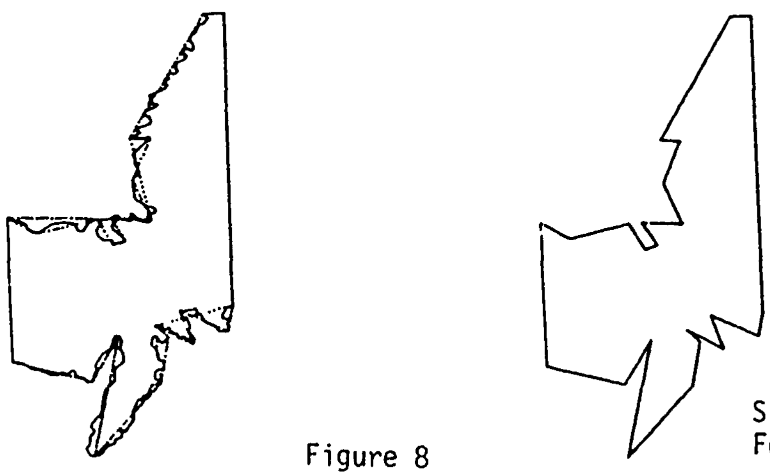
Another important software function imbedded in interactive culture is feature simplification. The user singles out particular features which he considers to have excessive detail and invokes automatic feature simplification. He specifies the percent edge reduction and the simplified version is presented superimposed on the original feature (Figure 8). He then may accept the simplified version or may iterate with a different percentage reduction.



EUF's prior to deletion

EUF's after deletion

Figure 7



Complex
Feature

Simplified
Feature

Figure 8

An additional sophistication is available in this function. "Sacred" vertices can be specified which will survive the feature simplification. This may be necessary for correlation with nearby features or to match a continuation of the same feature in adjoining culture manuscripts.

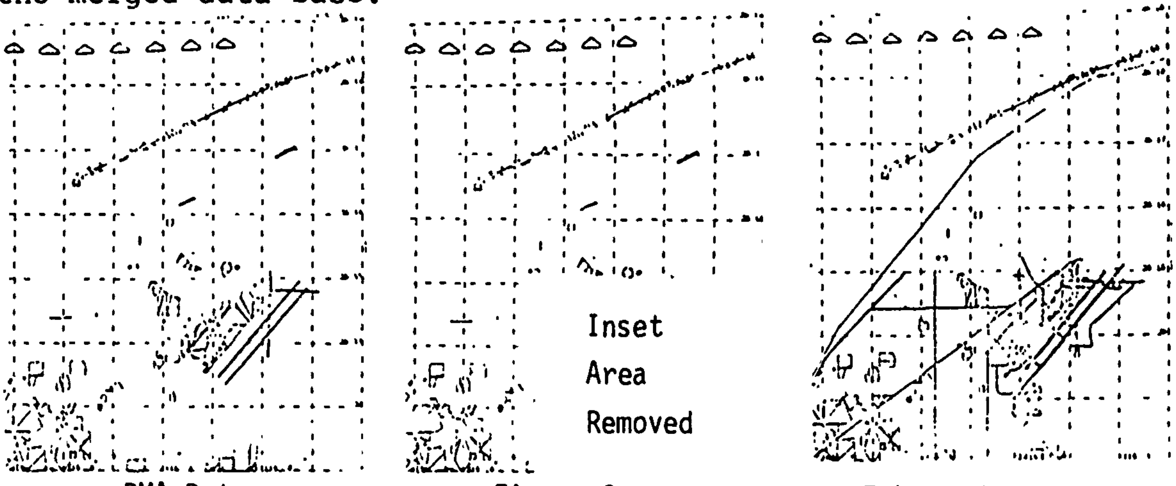
HIGH DETAIL INSETS

The C-130 program was the first to require not only a wide area data base (35,000 sq. mi.) but insertion of "high detail insets" into it. These insets typically represent an airfield, drop

zone, bombing range or other area of specific training requirements. GE has developed a technique to carve out a segment of the wide area data base, modify and enhance it and merge it back in. This approach allows the modeler to create the high detail inset in his own coordinate system but still guarantees consistency and smooth transition to the surrounding transformed data base.

The inset area can be defined in increments of 1.5' x 1.5' and expanded to include as many of these increments as the modeler wishes to hand model. The purging process not only deletes the inset area from the transformed data base, but preserves all the data from the inset area in a form suitable for manipulation by the modeler. Thus, he can retain or discard as much of the DMA data (both terrain and culture) as desired.

This techinque overcomes the coordinate system problem. He then models in his own coordinate system and is allowed complete flexibility within the inset area, constrained only to retain the boundary vertices so the inset will match the surrounding area. After merging of the inset back into the data base it is rotated back into geocentric coordinates for the IG. Figure 9 shows the initial transformed data, the purged area, the inset and finally the merged data base.



DMA Data — Figure 9 — Enhanced region

INTERACTIVE TERRAIN GENERATION

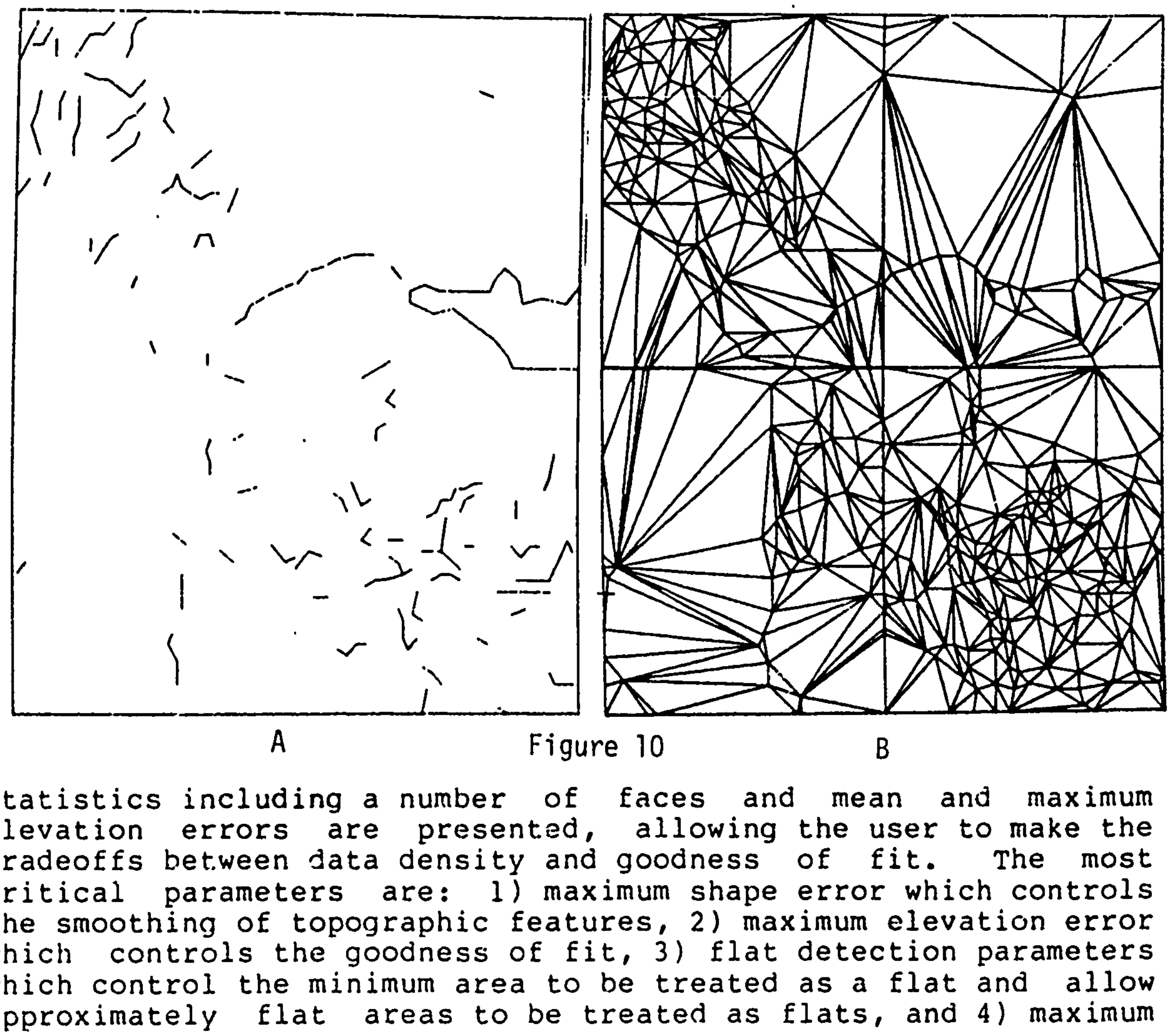
Interactive terrain generation is a recent development in the evolution of data base techniques. It contains an automated terrain generation process, but allows the user to manipulate the controlling parameters and to quickly see the resulting terrain in calligraphic plots. The response time is 15-30 seconds for a 6' x 6' area, fast enough to iterate many times before selecting the best results. This tool was used to create the VSCDP terrain.

As in the transformation program, the input is DMA elevation data. The user is presented a latitude, longitude grid and can select any available combination of regions for processing where a region can be defined as a 3' x 3', 6' x 6' or 12' x 12' area.

Once his area of interest is established all display and processing commands apply to the whole area.

This approach is founded on the presumption that certain topographic features (ridges, valleys, pits, peaks, flats) should be preserved in the data base. Therefore, as a first step it analyzes the source data and detects these features. Step 2 is to form a triangle network which includes all detected features, as triangle edges and vertices.

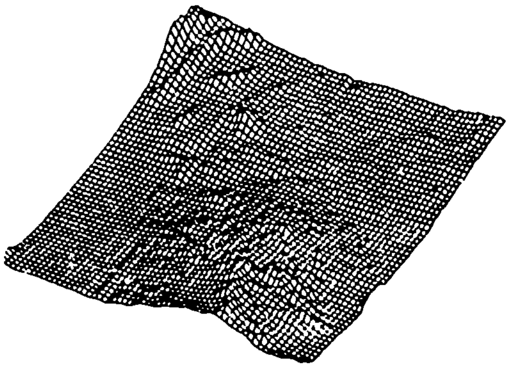
The user can then manipulate the automatic feature detection parameters or can digitize his own features. Figure 10A shows a typical topographic feature plot. Once satisfied with the topographic features the user sets up his triangulation parameters and initiates automatic triangulation. Figure 10B shows the resulting triangle network.



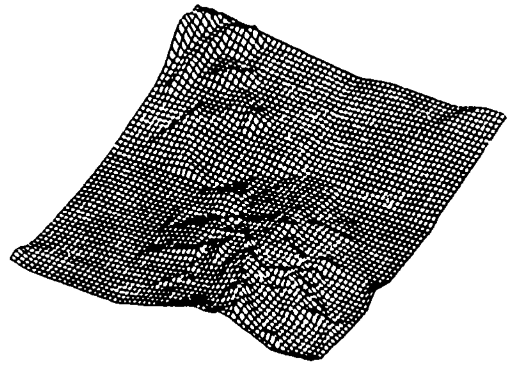
A Figure 10 B

Statistics including a number of faces and mean and maximum elevation errors are presented, allowing the user to make the tradeoffs between data density and goodness of fit. The most critical parameters are: 1) maximum shape error which controls the smoothing of topographic features, 2) maximum elevation error which controls the goodness of fit, 3) flat detection parameters which control the minimum area to be treated as a flat and allow approximately flat areas to be treated as flats, and 4) maximum face count.

Fishnet and contour plots are available for visual inspection and evaluation. Figure 11 presents the DMA source data and the generated approximation using 682 terrain faces.



DMA Data Plot



Simplified Approximation

Figure 11

INTERACTIVE MODEL CREATION

Recently GE has developed an interactive modeling tool that allows users to quickly define convex objects and assemble them into models, viewing the model in calligraphic form as it is created. Models that used to take a day can now be created in less than an hour. The tool relieves the modeler of tedious tasks of vertex and face definition and data entry. The system allows regular shaped objects to be easily constructed and assembled into models.

It also allows partial usage in conjunction with hand modeling. The user may hand model those parts of the model not ameanable to interactive creation and then modify or add new parts using this tool.

Objects are constructed from their base upwards, specifying the radius elevation and number sides of each level. Level 1 is normally on the ground, but this is not required. Each ascending level used the "roof" vertices of the previous level as its "floor" vertices. The structure may continue upwards for 16 separately defined levels. Figure 12A shows a space needle which was created in less than 5 minutes.

Note that the structure can terminate in a single peak. Rectangular structures are defined by length and width and may have two sided roofs as shown in Figure 12B. Structures can also be scaled in x and y directions, or each level can be offset. Figure 12C shows a crank created using the offset capability.

The software computes the vertex and face definition and analyzes the structure, dividing it into convex objects.

Multiple structures can be created and then moved into their proper relative positions. Although this can be accomplished with move and rotate functions, those require specific rotation and translate instructions. A "join" function is available which

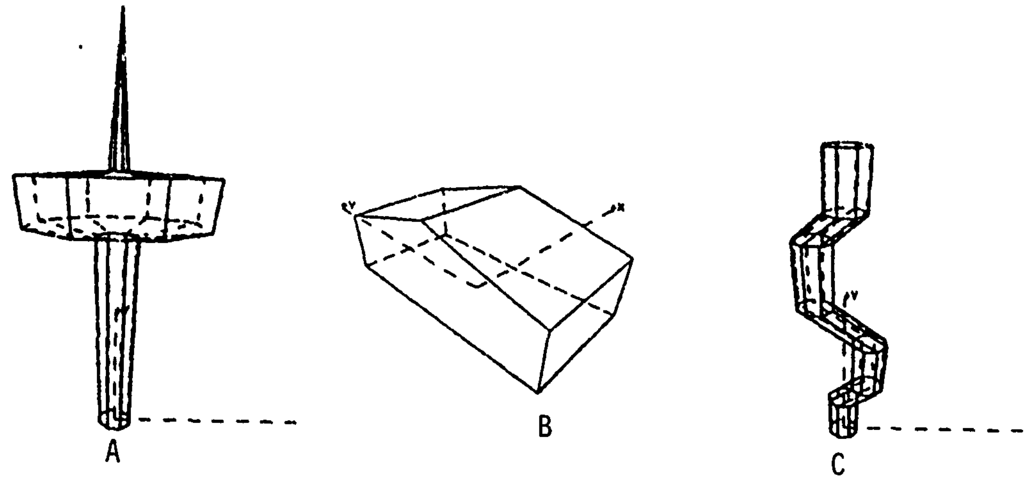


Figure 12

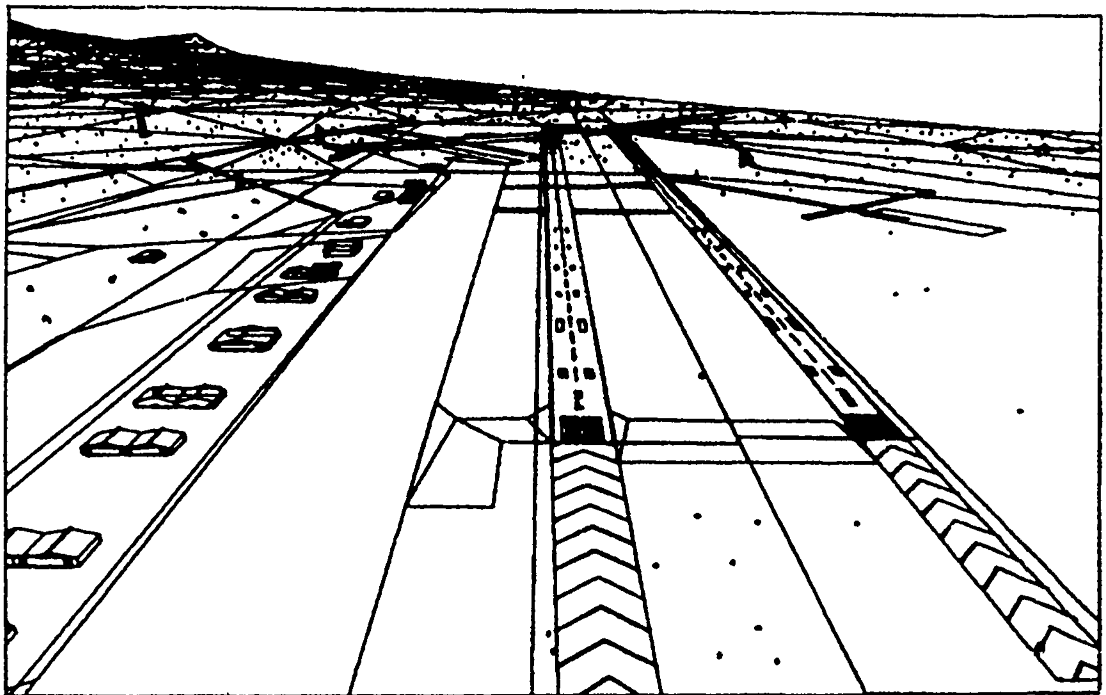
facilitates most moving tasks. The modeler merely specifies the faces to be joined together, and the software computes the necessary movement. An object can also be copied to multiple locations.

STORING AND VIEWING DATA BASES

In the last two years, GE has begun implementation of a standard data base format to alleviate repetitive software creation for every new simulator and to facilitate transfer of data bases from one system to another. Both AVTS and VSCDP are using this standard format and it is also planned for the next generation of Compuscene IV products. This standard data base format package consists of a "surface file" containing terrain and surface culture definition and 3D model locations plus a model library containing the actual 3D model definition. With standardization in place, users will be able to accumulate models and gaming areas which may be utilized on different programs. It should be noted that a post processor is still required for each new CIG system to combine the surface and model definition into the specific CIG usable format.

As part of the automated data base development process, viewing capabilities have been enhanced to facilitate trouble shooting and provide timely documentation of generated features. Off-line viewing is an essential part of data base creation and checkout. The plotting software package offers perspective, xy, fishnet and contour plot options. Figure 13 shows a perspective plot of the Nellis AFB data base being developed for AVTS.

Most geometric errors can be detected and corrected off-line using calligraphic plots. However, some important data base characteristics require on-line viewing and adjustment. Color, texture, activation range and blending are examples of characteristics to be evaluated and fine tuned on line. Several of our recent systems including B52, C-130, Compuscene III and AVTS have provided "interactive CIG" tools which allow on-line modifications to CIG memories with an immediate feedback on the CIG monitor. This technique offers great benefits in subjective areas such as color and texture tuning. A joystick is used to



Nellis Air Force Base Simulation
Figure 13

control a cursor on the CIG display which is placed on the feature to be modified. The joystick can then be used to interactively modify the color components or texture vectors of the faces in question.

SUMMARY AND CONCLUSIONS

The last five years have seen a revolution in both automated and interactive techniques to support the modeling process. The transformation program has evolved into an efficient off-line system which generates a wide area CIG data base from DMA source data "untouched by human hands". The modeler has three basic ways to control the results: 1) through parametric controls, 2) by enhancing the source data with additional features, or 3) by carving out segment of the transformed data base and hand modeling a high detail inset to replace it. Recent trends are to imbed the batch processing functions of the transformation into the interactive tools, allowing the user to experiment with parameter settings and quickly view the result.

By constantly improving modeling interactive capabilities as well as automated techniques, it will be possible to continue to provide effective real world data bases at the densities needed for military visual simulators.

SESSION III

Environmental Data Base Considerations
Part II

CAPTAIN LESTER T. JACKSON, JR., Session Chairman
Naval Education and Training
Pensacola, Florida

A native of Hampton Bays, New York, Capt Lester T. Jackson, Jr. received his commission and wings after his completion of the Naval Aviation Cadet Program in September 1957. Following pilot training he was assigned to Attack Squadron 106, home based at NAS Cecil Field, Florida, where he flew the F9F-8 Cougar and A-4B Skyhawk. While on this tour, Capt Jackson made Mediterranean deployments aboard Attack Carriers USS Essex (CVA-9) and USS Shangri-La (CVA-38).

Capt Jackson's next assignment was to Fleet Replacement Attack Squadron 44 at NAS Jacksonville, Florida, as an instructor pilot in F9F-8T and A-4C aircraft. Following this shore tour, he returned to sea duty as the Assistant Navigator aboard the Anti-Submarine Carrier USS WASP (CVS-19). In October 1966 Capt Jackson was reassigned to Attack Squadron 76 home based at NAS Lemoore, California. While on this tour he made a Western Pacific combat deployment aboard the Attack Carrier USS Bon Homme Richard (CVA-31) and a Mediterranean cruise aboard USS Independence (CVA-62).

Capt Jackson attended the Naval Postgraduate School at Monterey, California, where he received a BA degree in International Relations. Capt Jackson was then assigned Air Force/Navy exchange duty and served on the Headquarters Staff, Air Training Command, Randolf Air Force Base, Texas.

In September 1971 Capt Jackson was reassigned Attack Squadron 42 transitioning to A6 Intruder. Capt Jackson served as Executive Officer and then Commanding Officer of Attack Squadron 34 making two Mediterranean cruises aboard USS John F. Kennedy (CV-67). This tour was followed by a year of study at U.S. Naval War College and then in August 1975 assignment to the staff of Commander U.S. Second Fleet followed by a two-year tour starting in July 1978 on the staff of the Supreme Allied Commander Atlantic (SACLANT) where he was Director of Operations and Warfare. Capt Jackson's last duty assignment was Commander, Training Air Wing TWO, one of the Navy's Strike Training Wings. His present assignment is Assistant Chief of Staff for Warfare Training on the staff of the Chief of Naval Education and Training.

Capt Jackson flew more than 100 combat missions over Vietnam. He is the holder of the Distinguished Flying Cross and an individual Air Medal, as well as ten strike-flight Air Medals, three Navy Commendation Medals with the Combat V and the Air Force Commendation Medal. He has over 4000 flight hours and has logged over 745 carrier arrested landings.

GEOGRAPHIC SUBDIVISION AND TOP LEVEL DATA STRUCTURES:

COLUMBUS, MAGELLAN, AND EXPANDING CIG HORIZONS

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L. Charles Clark has been involved in the design and production of CIG data bases at Evans and Sutherland for 2 years, working primarily on top level design issues and strategies for modeling urban environments. He obtained a B.A. degree in geography from the University of Utah in 1980.

Michael R. Pafford

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Michael R. Pafford has been involved in the development of CIG data base top level design and modeling strategies at Rediffusion Simulation for 2 years. He recieved a B.Architecture degree from the University of Texas at Arlington in 1980.

GEOGRAPHIC SUBDIVISION AND TOP LEVEL DATA STRUCTURES: COLUMBUS, MAGELLAN, AND EXPANDING CIG HORIZONS

L. Charles Clark, Evans and Sutherland Computer Corporation
Michael R. Pafford, Rediffusion Simulation Incorporated

ABSTRACT

In the past, visual data bases for training pilots were constructed from a set of repeating squares of generic flat terrain modeled with very little detail which were intermittently overlaid with a limited number of three-dimensional (3D), highly detailed, and specifically modeled 'areas of interest'; i.e., airports, targets, etc. The resulting contrast in feature density between specific and generic regions caused training tasks such as visual navigation and target recognition to become trivial. Recent advances in CIG technology have made it possible to eliminate this negative training ~~by~~ accommodat~~ing~~ the production of very large map correlatable visual data bases of homogeneous feature density.

Inherent in the top level design of a visual data base is a strategy for geographic subdivision. This strategy is implemented in a top level data structure which is processed by the CIG hardware to determine which portions of a visual data base to display. The top level data structure also dictates how the visual data base must be modeled. Since a visual data base is typically constructed in a 3D Cartesian coordinate system, the problems historically associated with 'round to flat earth' map projections are also encountered in top level data structures. ~~In addition to these problems,~~ there are constraints imposed by the CIG system used.

We will review the standard methods of geographic subdivision and discuss their limitations when applied to current training requirements. We will explore a new strategy for geographic subdivision of a visual data base utilizing the military UTM and UPS grid systems and the leverage derived from innovative modeling techniques; i.e., semi-automatic generation of terrain using DLMS data, and strategies for reusing common scene elements. We will discuss how these concepts are currently being implemented into visual data base design and will show how an extrapolation of these trends can be applied to the problem of 'whole earth' navigation training.

INTRODUCTION

Because of the need for larger and more complex training environments, the pressure is on for larger data bases and bigger computer image generation (CIG) systems to process them. Increases in hardware scale will result in increased data base processing capacity. However, hardware costs money, and the limit of economic feasibility for brute force hardware solutions is fast approaching. Perhaps a better approach to providing larger data bases is to apply new data base design strategies which utilize existing or slightly modified hardware of current scale. The new strategies which are presented in this paper were developed using an Evans and Sutherland CT5A image generator.

MILITARY REQUIREMENTS

If the military was interested in training excercises similar to those of commercial airlines, military training needs would have already been addressed. The major

'enemies' that a commercial pilot must be prepared to deal with are the weather, mechanical and electrical failures, and his own inexperience. No one is trying to shoot him down, and he does not need to attack anyone or anything. But in addition to the standard commercial training needs, military training requires a variety of weapons effects and map correlatable terrain with high visual densities to support low altitude flight.

A military pilot must be trained to defend his aircraft against attack. The potential threats include surface to air missiles, antiaircraft artillery and guns, and hostile aircraft armed with guns and air to air missiles. To counter these threats, prudent evasive maneuvers now include flight at a variety of altitudes down to tree top level. In actual combat, the risks of low altitude flight are preferable to the much greater risk of exposure to enemy detection at higher altitudes. However, in training, the risks of low altitude flight are high enough to severely limit the amount of training that can be accomplished at realistic combat altitudes. Also, shooting at pilots so they can practice avoiding threats is not reasonable training. Because of these risks, final honing of combat skills in the past has often awaited actual combat conditions, a less than optimal situation.

A military pilot must also be trained to attack threats and targets. Because of the costs involved, pilots are allowed only limited experience in defensive and offensive weapons delivery; i.e., dropping bombs, and firing missiles and guns against ground based targets and threats. They are given almost no experience against moving air targets. Training in weapons delivery has also often awaited actual combat conditions.

These military training requirements can now be accommodated through simulation. To support low altitude flight and weapons delivery, a visual data base can provide high visual densities and sufficient navigational, altitude, and attitude cues to allow the pilot to focus his attention on threats and targets instead of on his instruments. Weapons delivery simulation can be accomplished through a variety of accurately modeled weapons effects. Terrain regions of interest are no longer limited to airports of operation as they are in commercial aviation training. The visual data base can include large contiguous geographic areas with map correlatable features; i.e., roads, bridges, cities, and factories which serve as navigational checkpoints, or as targets to be defended or attacked.

To support military training requirements, a visual data base must have some special characteristics. Its structure and content must promote efficient processing and high feature densities. The data base must also be carefully managed at run time to result in optimal use of the CIG hardware resources.

CT5A DATA BASE PROCESSING

Because of the hierarchical nature of CT5A data base organization, data base management is an implicit function of the data base structure. An organizational relationship exists between the data base structure and the gaming area geography. As a result of data base management, the data base is culled to the minimum amount of information required to define each visual display field (1/50 of a second) at run time.

A HIERARCHICAL DATA BASE TREE

A CT5A data base has the logical form of a hierarchical tree structure of branches, and decision nodes called cells. A cell is a volume in model space represented by a decision node in the data base tree. The primary function of a cell is to provide a choice between either a simple or a complex representation of some portion of the data

base, based on the distance between the cell and the viewer's eyepoint, or viewpoint. Either choice can consist of a null (the portion of the data base is so far away that nothing need be displayed), an object (a collection of scene elements; i.e., surfaces and light strings), or a collection of cells called a mesh. A mesh forms another branch of the tree which must be processed by the CIG, and is often used to subdivide a region of model space into several smaller regions. A mesh also contains rules for the visual ordering of its constituent cells.

Because the overall gaming area geography of a data base can be subdivided hierarchically into many smaller nested areas, cells in the data base tree usually have some geographic context. Tracing the tree from top to bottom, each successive hierarchical level has more cells, and the cells are associated with smaller geographic regions. The upper hierarchical levels, called the top level tree, contain cells which relate to large geographic regions. Lower levels of the tree contain cells which ultimately invoke the scene elements of visual models; e.g., the terrain surface, individual buildings, trees, etc. Within this hierarchical organization, culling and ordering decisions about major data base regions propagate automatically to smaller regions.

DATA BASE MANAGEMENT

Given a viewpoint with defined field of view constraints, data base management can be thought of as the process by which the CIG culls the data base, discarding all portions which are irrelevant to the current scene and processing the relevant portions which are left over. One approach to data base management is a hierarchical subdivision of the overall data base culling problem into a system of many nested simple problems.

The data base is stored on a disk which is hosted by a general purpose computer. Data base management is a two step culling process resulting in two subsets of data from the data base. The first subset is that portion of the data base which is transferred from disk to CIG memory because it is within the system visibility limit of the viewpoint. The second subset consists of the portion of the data base which may be within the display windows. This culling process is designed to eliminate, as early as possible, and in pieces as large as possible, those portions of the data base that need not be processed.

The first subset is culled from the top level tree by a hardware based algorithm called the Pager. The Pager traces the tree and discards all cells containing large geographic regions which are too far away to be seen from the viewpoint. The resulting subset of geographic cells is transferred from disk to CIG memory, and data transfers occur by direct memory access. This subset is continually changing as the viewpoint moves within the overall gaming area, but will generally represent a small fraction of the total data base. Changes in this subset occur at a low rate and are performed as a background task over multiple field times.

This approach to managing the disk/memory interface has several advantages over software based methods. First, the amount of work that the Pager must do is related not to total data base size, but only to the portion of the data base required for the specific viewpoint. Thus the Pager load is tied to local data base feature density, and order of magnitude increases in data base size cause almost insignificant increases in Pager work load. Second, the process of tracing the tree is very fast. Typically the entire on-line data base can be traced and update requests identified in much less than a second. Thus the system responds very rapidly to changing data base needs, and the total amount of data required to be on hand can be reduced to a minimum. Third, because the process is entirely driven by the data base structure itself, the

real time software needs to know very little about the data base to support its management.

From the first subset, the CIG extracts an even smaller second subset. This second subset consists of cells from the lower levels of the tree which ultimately invoke scene elements that may be within the display windows. The cells in this subset are ordered according to their visual priority and include only the simplest permissible representations of visual models reduced to those surfaces which are front faced and large enough to be useful in the displayed image. This second cull processes only the data which survives the first cull (and resides in the CIG), but it must be performed once every field. As a result of these culling operations, the CIG extracts those scene elements which are most useful to the viewer, while preventing the artifacts of this management from distracting the viewer.

The hierarchical tree structure of a CT5A data base and the real time data base management operations allow for very efficient data base processing by the CIG. Because of this efficiency, the CIG spends less time processing the top level tree, thus allowing more time to process the lower levels of the tree where the scene elements reside. The result is a visually correct image which has been optimized through careful data base management to promote maximum feature density. Since the implementation of these strategies, average scene element densities in production data bases have increased from a nominal average of 5 polygons per square nautical mile to over 2000. Such densities are continuously maintained throughout very large regions of modeled terrain.

GEOGRAPHIC SUBDIVISION

Because each cell in the top level tree is usually associated with a discrete geographic region of the data base, a strategy must be developed for subdividing the gaming area geography into a hierarchy of mutually exclusive and exhaustive geographic cells. The objective of the subdivision system is to reduce the data base, at some hierarchical level near the bottom of the tree, to geographic cells of a manageable scale. Such a system of geographic subdivision can be most effectively developed and implemented within the context of a map projection.

ROUND TO FLAT EARTH TRANSFORMATION

A visual data base is typically constructed in a 3D Cartesian coordinate system with the ground nominally parallel with the X-Y plane. In the process of modeling a real world data base, the terrain surface must be transformed from a round earth with spherical coordinates to a flat earth with Cartesian coordinates. Such a transformation is called a map projection. A map projection is a systematic transformation of the surface of a spheroid representing the earth to the planar surface of a map. It is impossible to make this transformation without distorting some of the natural geometric attributes of the spherical surface.

There are numerous common map projections, each of which minimizes distortion for some particular region of the globe. When mapping small geographic areas, the surface distortion introduced by round to flat earth transformation is small, and is usually considered insignificant for most applications. But as the mapped areas increase in size, surface distortion becomes the factor which limits the usefulness of the projection.

Military training requirements have translated into a current demand for very large and complex data bases which must be map correlatable to real world terrain. Because

the scale of current data bases is so large, the map projection selected for modeling terrain in a given region of the earth's surface must have acceptable distortion characteristics for that region.

THE ESSENTIALS OF GEOGRAPHIC SUBDIVISION

A system of geographic subdivision, developed within the context of a specific map projection, must have the following characteristics:

1. Geographic Reference - The discrete geographic regions associated with cells in the data base tree structure should have some geographic reference to the real world through source materials (such as maps, the Digital Landmass System (DLMS) data base, etc.) which provide information about the data base area. This is usually accomplished with some coordinate system already present in, or which can be added to the source material.

2. Hierarchy - The system should accommodate multiple levels of hierarchical subdivision. In other words, the cells with their associated geographic regions at a given level of the tree should be collectable into meshes; i.e., collections of cells which can then be nested into the cells associated with larger geographic regions at the next higher level.

3. Modularity - The system should accommodate an instancing strategy. Instancing allows a cell to be modeled about its own local origin, and then be positioned at its proper location in the data base by the use of a run time position vector. Instancing will work in the context of almost any system of geographic subdivision. However, a strategy for instancing large geographic regions, and having them fit together precisely, requires that the geographic subdivision be controlled by regular geometry.

4. Flexibility - The system should be adaptable enough to allow the shapes, sizes, and relative locations of cells to be adjusted to meet the qualitative expectations of the user. It should not be a rigid or arbitrary system that imposes unwanted divisions in logically contiguous geographic regions.

ALTERNATIVE STRATEGIES FOR GEOGRAPHIC SUBDIVISION

In the following discussion, six possible approaches to the problem of geographic subdivision are reviewed and analyzed in terms of their geographic reference, hierarchy, modularity, and flexibility. The first three alternatives are irregular boundary systems. The last three alternatives are grid systems.

Irregular Boundary Systems

Data base task regions are user defined geographic subsets of a gaming area within which specific training tasks are to be conducted. Often, modeling requirements for two task regions in the same data base are very different, resulting in practical modeling boundaries between them. Because task regions are usually irregularly shaped, their boundaries typically form an irregular polygonal pattern on a map.

Natural and cultural boundaries are linear geographic and cultural features; e.g., rivers, coastline, roads, etc. An irregular polygonal pattern of geographic subdivision emerges from the composite of these boundaries on a map.

Political boundaries may follow geographic and cultural features (rivers, coastline, roads, etc.) or they may be arbitrarily derived. Because political entities are usually irregularly shaped, their boundaries usually form an irregular polygonal pattern on a map.

Task regions, natural and cultural boundaries, and political boundaries all result in geometrically irregular subdivision systems. These systems can be referenced geographically; i.e., the boundaries are found on maps, and they can be thought of as hierarchical. But because of their irregular geometry, these systems are neither modular nor flexible.

Grid Systems

In the past, the most common strategy for geographic subdivision has been the application of an arbitrary rectangular grid system to maps of the gaming area. An arbitrary grid can be very convenient since the unit of measure, the origin, and the orientation of the grid can all be selected by the data base developers. Because of its regular geometry, a rectangular grid is hierarchical, modular, and flexible. But it can only have geographic reference if the grid is superimposed onto maps of the gaming area. On a major project covering thousands of square miles with detail required from 1:50,000 Defense Mapping Agency (DMA) and 1:24,000 United States Geological Survey (USGS) maps, the grid would have to be applied to several hundred maps.

The most familiar geographic grid system, the graticule, is derived from spherical coordinates with a reference grid composed of horizontal lines of latitude called parallels, and vertical lines of longitude called meridians (figure 1). All meridians are

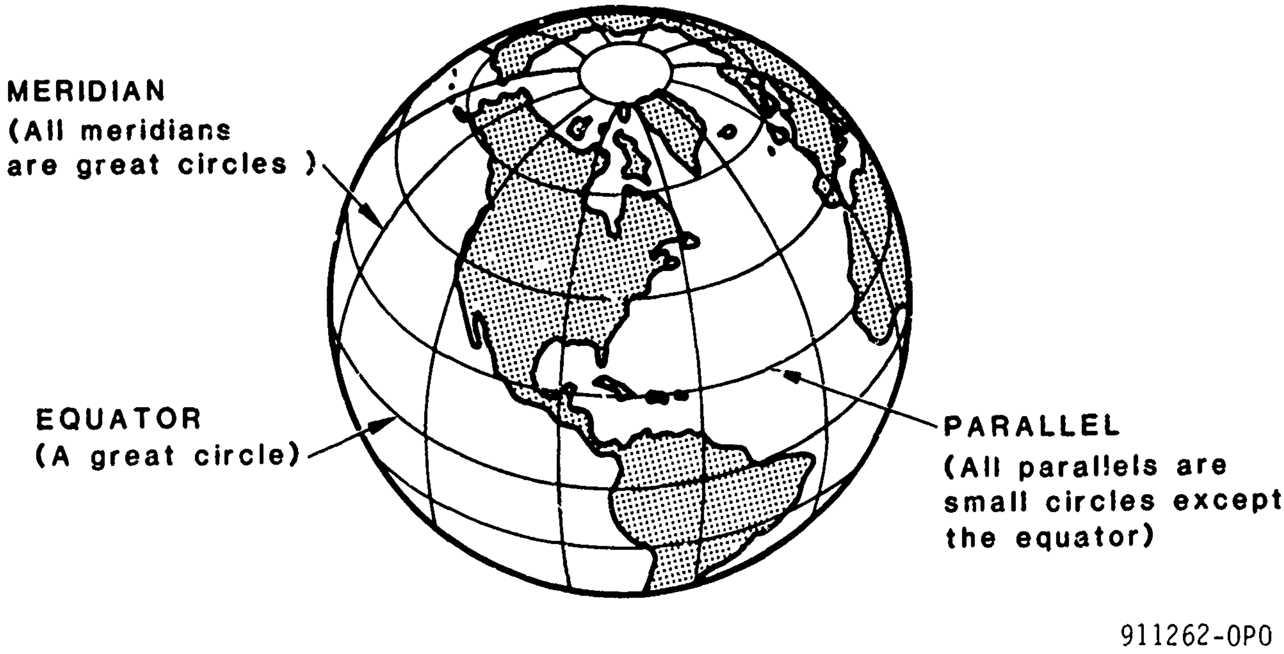


Figure 1. The Graticule

great circles which intersect both poles of the earth. A great circle is defined by the intersection of a plane with the surface of the earth such that the plane divides the earth into equal hemispheres. The only parallel which is a great circle is the equator. The equator is defined as the intersection of the surface of the earth with a plane perpendicular to the axis of the earth which also passes through its center. All other parallels are small circles parallel to the equator. In general, a small circle is a circle on the surface of the earth which is parallel to a great circle. The graticule is useful in comparing the geometric relationships of homologous points of the earth's surface before and after a transformation.

The graticule is associated with all map projections and is useful for navigation. Aircraft inertial navigation systems are referenced in spherical coordinates (latitude/longitude) as are the locations of navigation aids and airfields. However, when the graticule is transformed by a map projection, grid lines are often represented as curved or converging lines with variable distances between them. The resulting representation of the graticule on maps is typically an irregular grid. The graticule can be easily referenced on maps, and it can be thought of as hierarchical. But because of its irregular grid geometry in most map projections, it is neither modular nor flexible.

A less familiar class of geographic grid systems are known as rectangular coordinate systems. These coordinate systems, which are usually defined within the context of special purpose map projection systems, employ rectangular grids for geographic reference; i.e, the grid is found on maps in addition to the graticule. Algorithms typically exist for very accurate conversion between rectangular coordinates and spherical coordinates. Rectangular coordinate systems have all the essential characteristics of an optimal geographic subdivision system; they have geographic reference, and they are hierarchical, modular, and flexible. The most useful rectangular coordinate systems for geographic subdivision of a data base are the military Universal Transverse Mercator (UTM) and Universal Polar Stereographic (UPS) projection and grid systems.

The United States has adopted the UTM and UPS projection systems for large scale military mapping applications. The UTM system is used between latitudes of 84 degrees North and 80 degrees South while both polar regions are covered by the UPS system. The UPS system complements the UTM system, and there is an area of overlap along the boundary of the two. Maps produced by the military usually include the UTM or UPS grid in some form. For example, the blue grid lines superimposed on a 1:500,000 scale Tactical Pilotage Chart (TPC) represent a 50,000 meter UTM grid with 10,000 meter tick marks, and the black grid lines on 1:50,000 DMA topographic maps represent a 1000 meter UTM grid with 10,000 meter reference. In addition to military maps, some form of UTM reference is found on most USGS maps, and approximately 60 countries use the UTM projection system as an authoritative and general use map projection.

THE UTM PROJECTION AND GRID SYSTEM

The UTM projection is an enhanced version of the Mercator and Transverse Mercator projections. A basic understanding of these projections is a prerequisite for understanding the UTM projection system.

The Mercator projection is constructed by mathematically projecting the surface of a spheroid representing the earth onto the surface of a cylinder which encloses the

spheroid and is tangent to it along its equator (figure 2). The graticule is projected from the surface of the spheroid onto the surface of the cylinder. When the cylinder is cut open and laid out flat, the meridians are vertical straight lines which are parallel and equally spaced. The parallels are horizontal straight lines which are parallel with each other and perpendicular to the meridians, and the distances between them increase as latitude increases.

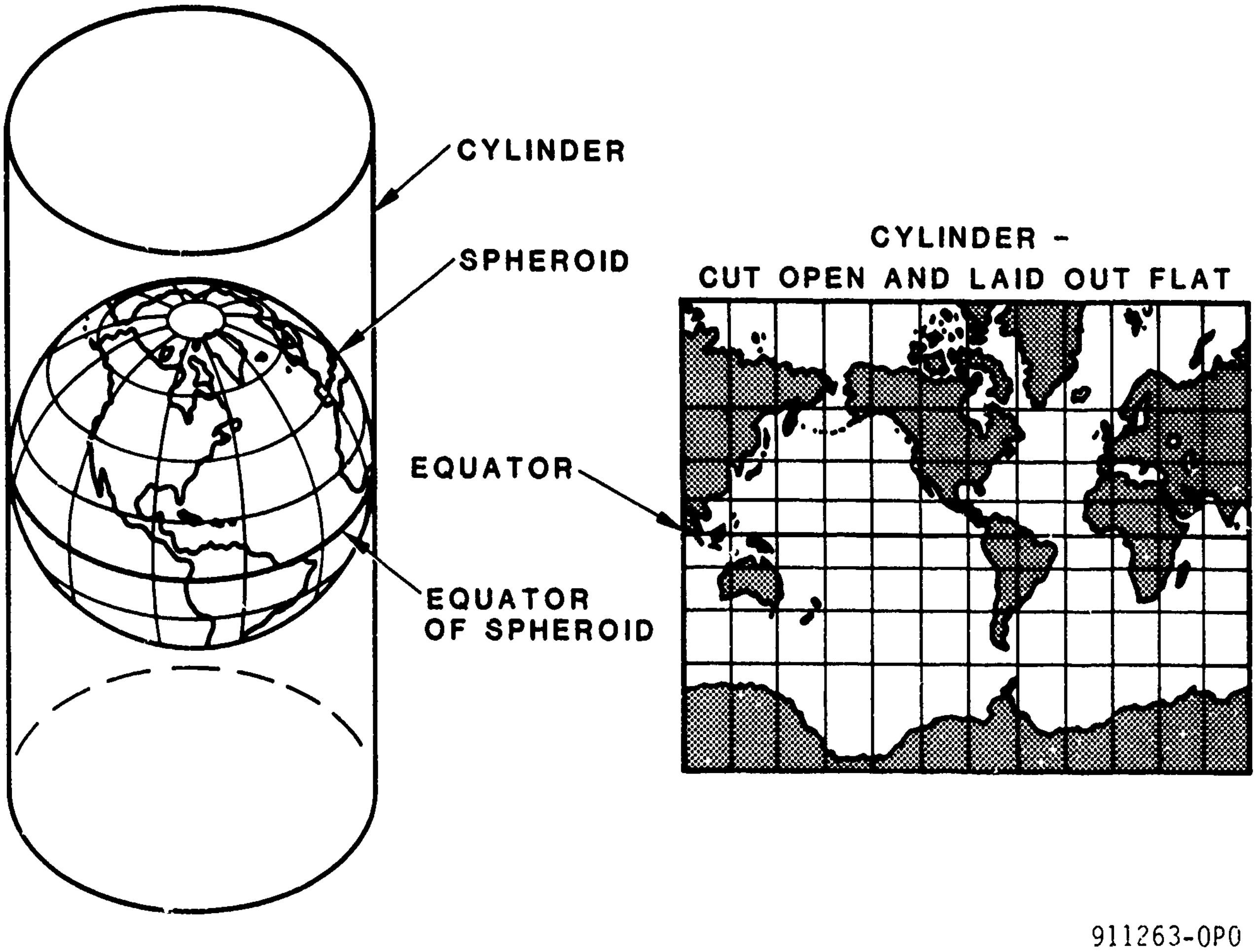


Figure 2. The Mercator Projection

A Transverse Mercator projection is constructed by rotating the cylinder 90 degrees so that it is tangent to the spheroid along a meridian (figure 3). Now when the graticule is projected onto the surface of the cylinder and the surface is laid out flat, the meridian of tangency is a vertical straight line. This meridian is the standard meridian of that particular Transverse Mercator projection. The equator, and the meridian which is perpendicular to the central meridian at the poles, are the only horizontal straight lines. All other meridians and parallels are curved lines.

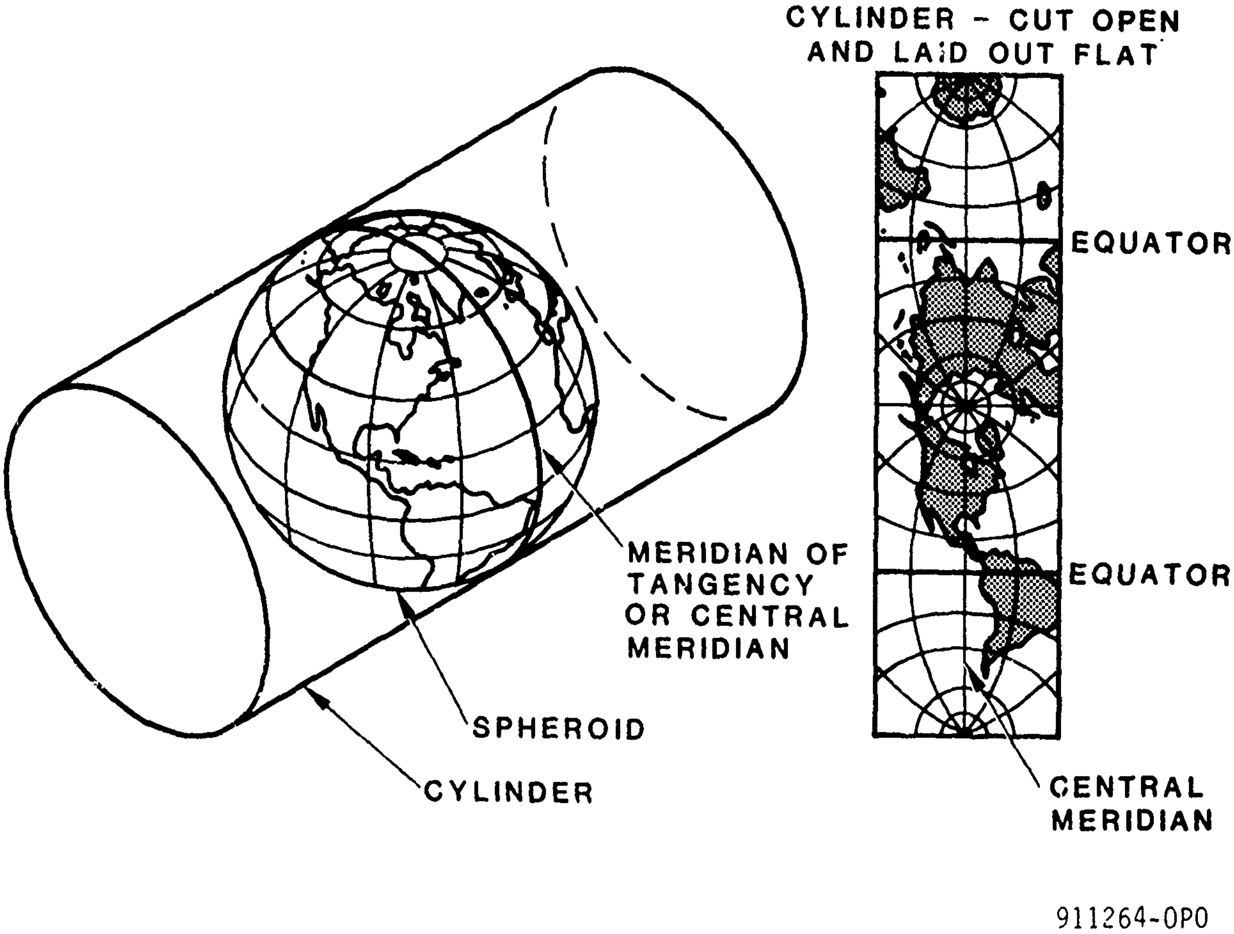


Figure 3. The Transverse Mercator Projection

The UTM projection is derived using concepts from the the Mercator and the Transverse Mercator projections. In the UTM system, the surface area of the earth between 84 degrees north latitude and 80 degrees south latitude is divided into 60 north/south columns of 6 degrees of longitude called zones. Each zone extends 3 degrees east and west of its central meridian. The zones are numbered consecutively from 1 to 60 beginning with the zone which is defined between 180 degrees and 174 degrees west longitude and continuing eastward. The UTM projection system is a set of 60 projections, with a transverse cylinder being secant to the spheroid along two small circles equidistant from, and parallel with, the central meridian of each zone (figure 4). When the graticule is projected onto the surface of the cylinder and the surface is laid out flat, the graticule looks virtually the same as it does in a Transverse Mercator projection.

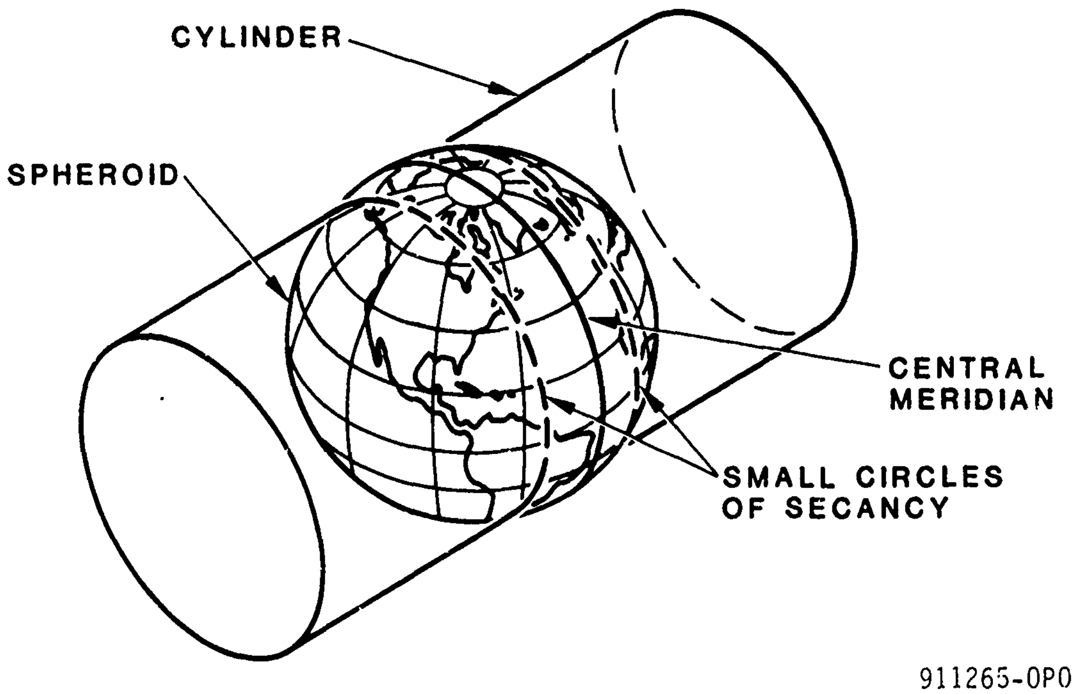


Figure 4. The UTM Projection

The central meridian in a Transverse Mercator projection is a standard great circle along which there is no scale distortion; i.e., the scale factor is 1.0000 (figure 5A). This results in a scale increase for longitudes away from the central meridian. A principal feature of the UTM system is that a scale distortion or grid scale constant of 0.9996 is applied along the central meridian of each zone with a scale factor of 1.0000 being applied along the small circles of secancy (figure 5B). Therefore, the longitudinal distribution of scale distortion in the UTM projection is more uniform than that of the Transverse Mercator projection. As a result, the UTM projection system has improved scale retention characteristics for geographic areas of significant longitudinal extent.

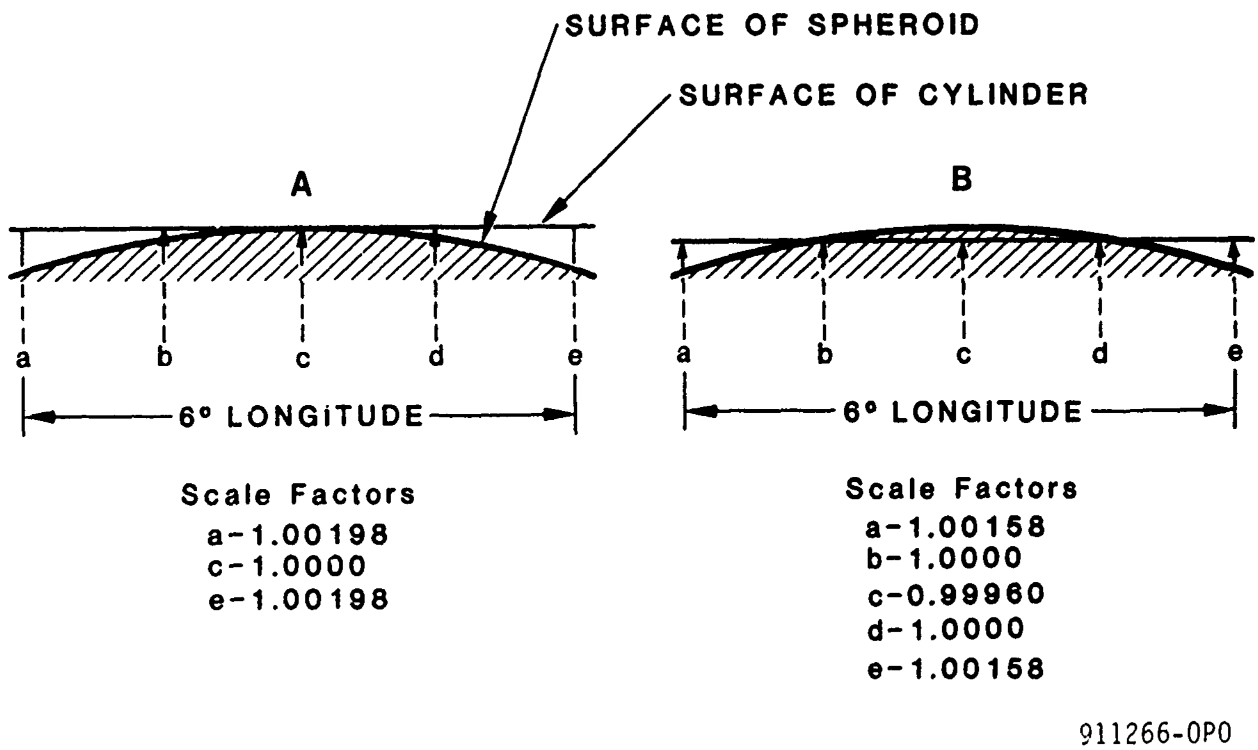
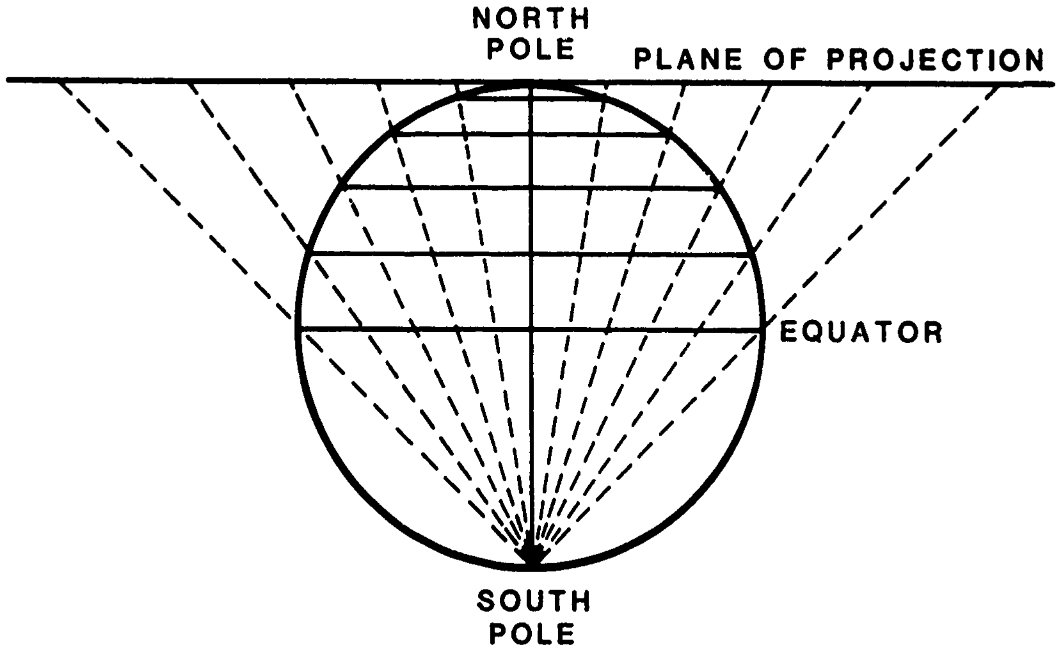


Figure 5. Scale Distortion in the Transverse Mercator and UTM Projections



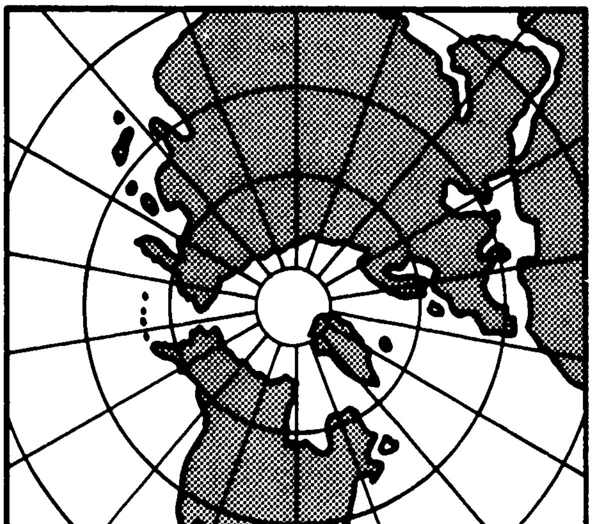


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Figure 6. The Polar Stereographic Projection

A rectangular metric grid is aligned with the central meridian of each zone. The central meridian is given an arbitrary false easting of 500,000 meters. This means that easting values for point coordinates east of the central meridian will be greater than 500,000 meters and that the easting values for point coordinates west of the central meridian will be less than 500,000 meters. For the northern hemisphere, the equator is given a northing value of 0 meters. This means that northing values for point coordinates north of the equator will be greater than 0 meters. For the southern hemisphere, the equator is given a northing value of 10,000,000 meters. Depending on the scale of the map, the UTM grid resolution may be as high as 1000 meters. This simple arrangement eliminates negative coordinate values. Transformation from one zone to another is according to uniform formulas.

THE UPS PROJECTION AND GRID SYSTEM

The UPS projection is an enhanced version of the polar stereographic projection. The point of projection in the polar stereographic projection is on the surface of the spheroid at the pole opposite the polar region being mapped. The surface of the spheroid is projected onto a plane which is tangent to the spheroid at the pole (figure 6). Thus if the region of the North Pole is being mapped, the projection is from the South Pole onto a plane which is tangent to the spheroid at the North Pole. The meridians are shown as straight lines radiating at their true angles from the pole, and the parallels are represented as concentric circles about the pole. The spacing of the parallels increases as they recede from the poles.

At the point of tangency (the pole in the polar stereographic projection), there is no scale distortion and the scale factor is 1.0000 (figure 7A). This results in scale increases for latitudes away from the pole. In the UPS projection, the surface of the

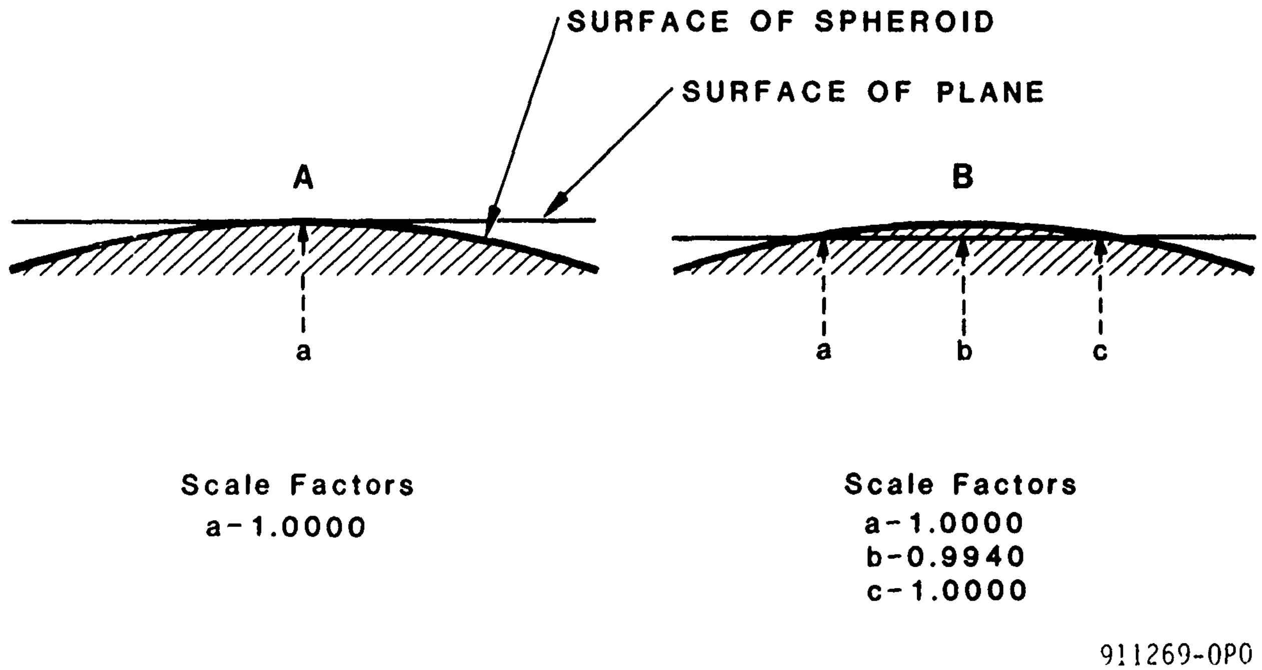

Figure 7. Scale Distortion in the Polar Stereographic and UPS Projections

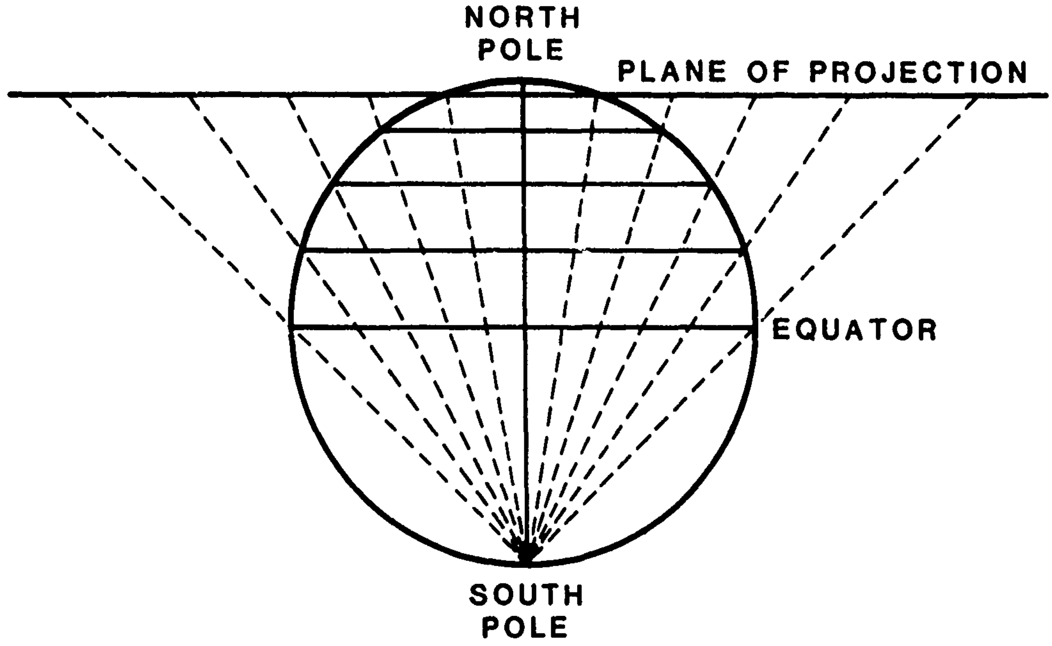

Figure 8. The UPS Projection

spheroid is projected onto a plane which is secant to the spheroid along the standard parallel of the polar region being mapped; i.e., about 81 degrees 7 minutes north or south (figure 8). A principal feature of the UPS projection is that a scale distortion or grid scale constant of .9940 is then applied at the pole and a grid scale constant of 1.0000 is applied along the standard parallel (figure 7B). Therefore, the distribution of scale distortion in the UPS projection is more uniform than it is in the polar stereographic projection.

The UPS system superimposes a rectangular metric grid over the polar areas with 90 degrees East/West being the horizontal axis and 0 degrees/180 degrees being the vertical axis. The 0 degrees meridian is uppermost in the south polar grid and 180 degrees in the north polar grid. Each pole is given an arbitrary northing and easting of 2,000,000 meters.

MODULAR TOP LEVEL DESIGN (TLD)

From an end user's perspective, a visual data base is usually described in terms of its real world domain; i.e., geographic boundaries, operational altitude ranges, required scene content, and purpose or mission. Often when the user's description is quantitative, the intent is to communicate to the data base designer the qualitative expectations for training. The data base designer's first tasks are to assimilate the user's description of the data base and interpret the qualitative intent. From this information, a top level data base tree can be designed and a system for geographic subdivision can be devised. The result of this process, called the Top Level Design or TLD, is a comprehensive plan for the production and implementation of a data base.

The system of geographic subdivision and the top level tree, which are essentially two manifestations of the TLD, become the organizational constructs within which the data

base is actually built. As an analogy, the TLD may be thought of as a pegboard, each hole of which is unique. The production of the data base may be thought of as the process of creating the pegs and inserting them into their corresponding holes in the pegboard.

BASIC MODELING SOFTWARE

As a result of the data base modeling process, data base source files are created to describe the structural and visual geometry of the data base. In large data bases, a large number of data base modules are defined by source statements contained in a large number of data base source files. These data base modules are compiled by the data base compiler into data base object files.

The data base linker generates, from the compiled data base modules, an absolute data base of the form required by the CIG hardware and the real time software. The linker is capable of constructing the data base in an incremental fashion. This allows the modeler to build modules of the data base and integrate them into the operational data base without having to redefine the entire model. The modeler may also replace, add, or delete modules without having to relink the entire data base, and elapsed times for multiple compiling and linking operations are measured in minutes or hours, rather than days. This is an extremely important feature in the production of large data bases where frequent changes are required.

MODULAR DATA BASE PRODUCTION AND REVISION

In the data base production process, the modular data structures of a data base may be exploited by defining each geographic cell as a data base module. Tasks can then be allocated in units of geographic cells, and several modelers can work independently and simultaneously on different modules. Because the TLD includes modeling standards and an exhaustive description of boundary conditions between geographic cells, the individuals in a modeling team can produce uniform results.

When the modeling for a geographic cell is completed and its source files are compiled, the module is linked into its predetermined place in the data base. As more and more modules are linked into place, the data base emerges incrementally as a growing set of geographic cells. When all modules are completed and linked in, the data base is complete. If revisions or enhancements to a geographic cell are desired, new source files for the module are created and compiled, and the new version is linked into the existing data base.

THE EVOLUTION OF TLD BASED ON UTM

The evolution of TLD strategy based on a UTM grid has been project related. The use of UTM grids has been applied to successively more difficult data base design problems. In retrospect, each successive application has moved this TLD approach toward a more general and globally applicable solution. The stages of this trend are discussed below.

THE FIRST APPLICATION

The UTM grid based modeling approach was first used in the design of a data base for the Air Force F-15 Limited Field of View (LFOV) evaluation at the Goodyear Aerospace Facility in Akron, Ohio. The evaluation process was scheduled for completion in March, 1984. This data base covers a small geographic region of about 80,000 square miles or approximately 280 X 280 nautical miles square. A 30 X 150 nautical mile

corridor of specifically modeled terrain extends from Seymour-Johnson AFB, North Carolina to the Dare County, North Carolina, Conventional Target Range. This map correlatable terrain lies in one UTM zone.

In this data base, the UTM grid can be thought of as a translation and scaled correspondence to the CIG grid. The origin of the UTM grid is at the equator while the origin of the CIG grid is on the west boundary meridian at a convenient latitude within the data base, and the UTM grid uses units of meters while the CIG grid uses units of feet.

Because the geographic area encompassed by the data base boundaries is virtually flat (no mountains), a flat earth modeling approach was used. There was, however, a requirement for an area of generic mountains in the data base. The terrain was subdivided into 10 km squares and each square in the data base was defined within the UTM grid of the zone to which it belongs.

The UTM grid was used as the construction grid of the data base. To make the flat terrain map correlatable, many important visual navigational cues were included in each terrain square. These cues included roads, coastline, cities, airfields, etc., and were modeled by instancing from a basis set. A basis set is defined as a set of scene components which exhaustively satisfy a class of local boundary conditions. Elements from this set can be used wherever they are required, and each element may generally be used numerous times in various places within the data base, even though it is only modeled and stored once. The basis set notion, which is a strategy for reusing common scene elements in a data base, provides great modeling leverage.

THE SECOND APPLICATION

UTM grids were next used in the design of a very large data base which is now in production. This data base will be used for AV8B operational flight and weapons tactics training at MCAS Cherry Point, North Carolina, and is scheduled for completion in June, 1985. The data base will cover a nominal geographic area of about 270,000 square nautical miles or approximately 520 X 520 nm square. About 25% of the data base is map correlatable to a contiguous geographic region of eastern North Carolina and Virginia covering parts of two UTM zones. In the data base, this map correlatable terrain is completely surrounded by generic terrain and ocean.

The juxtaposition of two UTM projections in a single data base must be carefully handled. In any given UTM zone, the only meridian that can be represented as a straight line is the central meridian. All other meridians are represented as curves including the eastmost and westmost boundaries of the zone, but the curves are so subtle that the meridians are often thought of as converging straight lines. The boundaries converge toward the central meridian as latitude increases with theoretical intersections at the poles. As a result of this convergence, the central meridian of each zone is not parallel to the zone boundaries except theoretically at the equator where all meridians may be said to be perpendicular to the equator and parallel with each other. Also, the intersection of the rectangular UTM grid with a boundary meridian results in a variety of clipped square areas; i.e., irregular pentangular shapes, trapezoids, and right triangles. Because of their irregular geometry, the clipped squares must be modeled specifically, so basis sets and instancing are of limited application.

To merge two UTM zones into an exhaustive and mutually exclusive area, they are inclined toward each other so that the angle of convergence of their central meridians is defined conceptually as 6*sinA where 'A' is some convenient latitude near the center of the gaming area. The zones are then juxtapositioned along the common boundary

meridian such that they partially overlap with the gaps at the top and bottom of the data base being approximately equal in dimension to the overlap in the center of the data base (figure 9). The gaps result in local surface expansion and the overlap results in local surface compression in the terrain model. In this data base, the dimension of the gaps and overlap is approximately 300 feet which amounts to about 1/16 of an inch on a 1:50,000 map.

In the data base, the y-axis (vertical) of the CIG grid system is colinear with the common boundary meridian between the two adjacent UTM zones. Each of the UTM grids can be thought of as a rotation, translation, and scaled correspondence to the CIG grid. Each UTM grid is rotated relative to the boundary meridian. The origin of each UTM grid is at the equator while the origin of the CIG grid is on the boundary meridian at a convenient latitude within the data base. Each UTM grid uses units of meters while the CIG grid uses units of feet. As a result, the two UTM grids are butted together along the common boundary meridian and that composite is overlaid on the CIG grid.

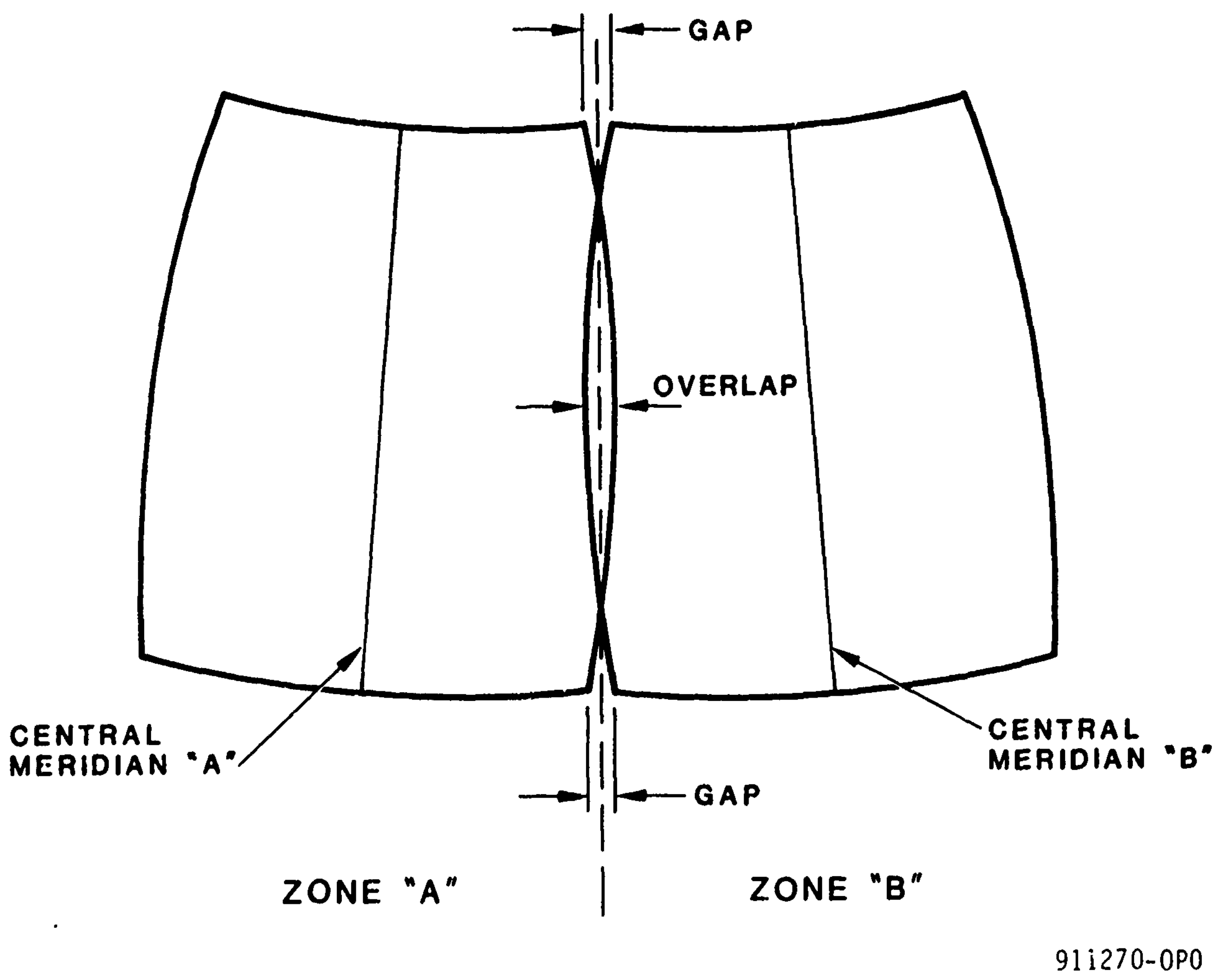

Figure 9. The juxtaposition of two adjacent UTM zones in a single data base

The geographic area encompassed by the data base boundaries is virtually flat. A flat earth modeling approach, allowing for some isolated relief perturbations, is being used. The terrain is subdivided into 10 km squares or clipped squares. Each square or clipped square in the data base is defined within the UTM grid of the zone to which it belongs.

The two UTM grids are used as the construction grids of the data base. Because each UTM grid has a unique rotation relative to the CIG grid, it requires a unique rotation of a theoretical common basis set. This is because basis set elements are instanced into place relative to one or the other of the two UTM grids, and the transformations allowed by the hardware for instancing include only translations, not rotations or changes in scale. Map correlatable navigational cues are modeled by instancing from the basis sets.

THE THIRD APPLICATION

Significant evolution of the UTM grid based modeling approach has occurred in its application to the preliminary design of a third data base in a more recent project. This data base will be used for AV8B operational flight and weapons tactics training at MCAS Yuma, Arizona, and is scheduled for completion in June, 1986. Like the second data base, this data base covers a very large geographic area, about 240,000 square nautical miles or approximately 600 X 400 nm square, but with a four-fold larger map correlatable geographic area. And like the second project, this data base crosses a UTM zone boundary, thus including portions of two UTM zones covering parts of southern California, southern Nevada, and western Arizona.

The terrain of the data base is subdivided into 20 km squares and each square in the data base is defined within the UTM grid of the zone to which it belongs. Important visual navigational cues are modeled by instancing from a single basis set. In addition to these navigational ques, a 3D terrain model is required. This is because the geographic area encompassed by the boundaries of this data base has some very mountainous areas. To automate the task of terrain modeling, an algorithmic (or procedural) approach to terrain model generation utilizing Digital Terrain Elevation Data (DTED) from the DLMS data base is being implemented This terrain generation procedure requires a set of terrain surface elements to be added to the basis set.

Unlike the second data base which spliced two UTM zones together and resulted in two unique modeling grids, the two zones in this data base are thought of as separate data base entities in the preliminary design. In each of these data base entities, the y-axis (vertical) of the CIG grid system is colinear with the central meridian of the zone. Therefore, each of the UTM grids can be thought of as a parallel translation (not a rotation) and scaled correspondence of the CIG grid. The origin of the UTM grid is at the equator while the origin of the CIG grid is on the central meridian at a convenient latitude within the data base, and the UTM grid uses units of meters while the CIG grid uses units of feet.

In a given visual display field at run time, only one of the two data base entities is displayed by the CIG. As the viewpoint crosses the boundary meridian from one zone to the other, the data base entity being visually displayed by the CIG is swapped from one to the other. To accommodate this swap, some special design considerations are required. For each of the two data base entities, the terrain model is extended beyond the UTM zone boundary into the adjacent UTM zone for a distance at least equal to the maximum visibility limit of the CIG. This terrain model extension for each data base entity functions as a visual transition buffer between data base entities. This means that when the viewpoint reaches the UTM zone boundary as it travels from one data

base entity to the other, the edge of the 'world' is never in view. Even at the UTM zone boundary, the terrain model extension results in visually displayable terrain out to maximum visibility. Although this strategy of multiple data base entities results in some redundant modeling (i.e., the terrain model extension for one data base entity will include terrain already modeled in the other), the tradeoffs are attractive. Because the UTM grids are not rotated relative to the CIG grid, a common basis set can be used by both data base entities. And because of the visual transition buffers, there are no clipped squares to be specifically modeled.

CONCLUSIONS

If historical trends continue, future training requirements will demand ever larger and more complex data bases. The evolutionary direction of UTM grid based TLD development can be extrapolated to predict future applications. It is conceivable that the current strategy for dividing a large data base into two data base entities could be extended to a modular system of multiple data base entites, or multiple data bases, covering contiguous map correlatable areas several orders of magnitude larger than current data bases. Such a multiple data base strategy could utilize hardware of approximately current scale.

To extend the order of magnitude increase to its logical maximum, we can conceive of literally modeling the whole world. Utilizing a multiple data base strategy, each of the data bases could contain a model of some relatively small portion of the earth's surface. The UTM Grid Zone system supplies this additional level of hierarchy. Each of the 60 UTM zones is divided into 20 grid zones, and each grid zone encompasses an area typically 8 degrees of latitude by 6 degrees of longitude of the earth's surface (with some exceptions). There are 1197 grid zones in the UTM system plus 2 UPS grid zones for a total of 1199 data bases, rounded for convenience to 1200. Because 71% of the earth's surface is ocean covered, many of the 1200 grid zones could be largely represented by a repeating pattern of water.

A terrain model for the area of a grid zone could be accommodated in a single data base compatible with current CIG systems. Such a data base would be nominally composed of two sets of 128 data files. In the first set, each file would occupy 576 disk blocks for a total of 73,728 blocks for the set. Each file in the second set would occupy 896 disk blocks for a set total of 114,688 blocks. Summing these set totals, a data base of 188,416 disk blocks multiplied by 512 bytes per disk block would result in a nominal data base size of 96,468,992 bytes. Of course, the data bases containing large areas of ocean would probably require much less disk space. With an additional small amount of space required for several ancillary data files, system diagnostics, and real time programs, the total overhead for a single data base would round out at about 100 megabytes maximum.

Assuming 1200 data bases at a maximum size of 100 megabytes each, a total of 120,000 megabytes of disk capacity would be required. If a set of 5 data bases could be stored on a single 500 megabyte disk, 240 disk drives would be required to keep the entire multiple data base system on-line. One alternative to 240 disk drives would be to store the 240 data bases, in sets or individually, on cartridge disks. Because no more than 4 of the 1200 grid zones ever intersect at a single point, no more than 4 data bases would need to be traced simultaneously by the CIG. 'Whole earth' navigation could then be supported by 4 disk drives and an operator to swap the disks.

Some other issues would have to be confronted to make a multiple data base strategy viable. The real time system would have to be capable of selecting the appropriate data base depending on the latitude/longitude position of the aircraft. And visual

transition buffers would have to be modeled along all the boundaries of all the grid zones to accommodate the switching between data bases. But the real challenges in this strategy result from its scale. For example, if the landmass to be modeled was limited to North America, the modeling process would need to be completely automated; even highly interactive modeling techniques would involve too much expensive manpower. A conceivable basis for such complete automation would be the DLMS data base. In addition to the terrain elevation information available through DTED, information is provided through Digital Feature Analysis Data (DFAD) about navigable cultural features. While DFAD in its current form has limited value for computer generated visual imagery, planned updates and revisons of the data will result in very usable information for generating visual data bases.

It is unlikely that a single user will ever need such 'whole earth' navigation capabilities. However, the demand for much larger gaming areas is here and now. A more probable configuration of the multiple data base strategy including some small set of on-line data bases, or some set of cartridge disks supported by up to 4 disk drives, is feasible. Current and near future projects will require that a strategy for solving the 'whole earth' navigation problem be at hand.

ACKNOWLEDGEMENTS

Many individuals in the E&S/RSI environment have contributed to the development of the strategies presented in this paper. We would like to thank the entire AV8B Data Base group for their contributions to the work which led to this paper, and for their help with the paper itself. We would like to especially thank Mike Cosman whose ongoing direction and key insights have been very much appreciated. We also thank Kyrt Patrick Lane for his suggestions and assistance in preparing the manuscript, and Dennis Gwynn for his work in preparing the illustrations.

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CIG DATA BASES

IN AN INSTANCE:

BITS AND PIECES

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ABSTRACT

The development of computer image generator (CIG) data bases covering large geographic expanses with a one to one correspondence of real world data is now required by many simulation scenarios. At first impression, this requirement indicates massive data base development costs and unending amounts of on-line data storage units. Further examination, however, reveals that strategies may be developed to reuse bits and pieces of CIG data base models and map them throughout the data base to create a one to one real world correspondence. The net effect is that data base development costs are reduced and the amount of required on-line data storage is decreased. Further, scene densities may be increased to take full advantage of image generator capabilities and are not degraded by lack of on-line storage availability. This notion implies that there exists a library of CIG models of standard cultural features that may be mapped or "instanced" throughout the geographic region. Further, the geographic region itself is a terrain model made up of instanced pieces derived from the Digital Landmass System (DLMS) data base, Digital Terrain Elevation Data (DTED). Another implication is that the image generator (IG) is capable of run time replication of these models throughout the data base. This concept of a library of cultural features ties closely to data provided by the Defense Mapping Agency (DMA) in the (DLMS) data base, 2nd Edition as well as the prototype specification to support High Resolution/Terrain Anaylsis Applications. This paper will show methods used to develop a collection of "Bits and Pieces" of real world cultural features and how to use information from DMA data tapes to map these features onto the terrain. The nature of the IG hardware used to achieve these results will also be discussed.

INTRODUCTION

As IG technology progresses and the complexity of the visual scenes grow, more and more is expected of the data base that is constructed for a particular simulation. IG data bases are now being constructed that cover gaming areas in excess of 70,000 square nautical miles (sq. n.m.). These large area data bases exhibit a one to one real world correspondence with navigable cultural and terrain features. This provides increased training effectiveness. A pilot can plan a sortie into the 'real world' using tactical air navigation charts for the area modeled and expect to find initial points, turn points and weapons delivery areas as depicted on standard charts. Further, the mission training is enhanced by allowing sorties into a wide range of areas with many options for diversion or alternate targets. It is expected that the demand for increasingly large data bases will continue. These data bases will serve not only the tactical fighter role but also strategic airlift and strategic weapons delivery.

THE CHALLENGE

A strategy for modeling data bases must consider the wide variety of missions to be supported. For many years the prime function of visual systems was to train takeoffs, landings and some limited flight operations. Data base development for this type of flight environment was relatively straight forward due to the limited areas being modeled. Costs were easy to identify and storage requirements for the data base were fixed due to the scope of the data base. The airfields were modeled to great complexity while the surrounding terrain was very sparse and largely generic. As image generator technology grew, visual simulations moved away from the local airport operating area. Various mission options were explored to include air to ground tactics, tactical navigation, counter threats, air to air tactics, helicopter NOE, in-air refueling, and normal flight operations, such as takeoff and landing. Each of these missions vary greatly in design requirements for the visual data base as well as the image generator itself. Attack helicopter missions must include sufficient optical flow in the data base to allow nap of earth (NOE) flight at speeds in the 30 to 100 knot range, while a mission for a terrain following strategic bomber must provide the cues necessary for near supersonic speeds at altitudes of less than 500 feet above ground level (AGL). Robert W. Beck identified major critical system characteristics that may be required for any particular mission simulation[1]:

1. Large field of view
2. High Resolution
3. Large gaming area
4. High scene content
5. Special effects

The system requirements differ for each training task. High altitude air combat may require only large field of view and high resolution, while low altitude tactical navigation may require all of the critical system characteristics. The task of defining data base requirements becomes formidable when considering complex training tasks. How large should the data base be? What are sufficient scene densities for the training task? What is the modeling effort? How much will the data

base cost? How much disk storage will the data base occupy? What will be used as source material for the data base? All these questions must have coherent answers prior to embarking on a massive data base development program.

FACTORS AFFECTING THE DEVELOPMENT OF THE DATA BASE

Many issues act together to affect the cost and complexity of data bases that cover a large gaming area and contain high scene content. One of the most important of these issues is the optical flow provided in the visual scene. The density and types of cues necessary to support flight at the designed airspeed and altitudes must be carefully evaluated in concert with aircrews expected to use the system. The visual scene must be made sufficiently rich in two-dimensional (2D) and three-dimensional (3D) cues. This may mean scene densities in excess of 1,000 to 2,000 polygons per square (sq.) nautical mile (n.m.) for tactical fighter missions or even scene densities in excess of 500,000 polygons per sq. n.m. for NOE flight. The issue of scene densities remains a clouded one with much work remaining to be done in determining optimal optical flow requirements for a particular mission. It is sufficient to say that high resolution and edge capacity do not automatically compensate for poor scene content.

High scene content and a large gaming area present a significant problem in data base development costs. Small area data bases were relatively easy to cost, as the modeling effort had a limited scope and the number of surfaces modeled were small. On the other hand, the effort to produce a 250 x 250 n.m. data base for a tactical fighter at a modest density of 1,000 polygons per square nautical mile requires 62.5 million polygons. If the data base development costs were measured solely by polygon production, it would take over 250 man years of effort to produce this data base at a rate of 1,000 polygons per man per day. There are of course other factors that enter into data base production costs, but it is true the development costs are high and difficult to accurately project.

Physical storage of the on-line data base is another problem to be solved in the development of large gaming area data bases. It takes about 200 bytes of memory to represent each polygon in the Evans & Sutherland CT5A data bases. If a 167 megabyte Digital Equipment Corporation RP06 disk is packed with 100% efficiency, it will hold 835,000 polygons. Even at these improbable packing rates it will take almost 75 RP06 disk packs to hold the modest 250 x 250 n.m. data base containing 1,000 polygons per sq. n.m. Assuming that this solution is unacceptable, there are three options available for producing this data base. First, restrict the number of polygons so that the data base is contained on only one RP06. At 100% packing efficiency, the number of polygons available for each square mile of the data base is reduced to about 13 per sq. n.m. Clearly this would provide unacceptable visual scene content. Second, reduce the polygon density by providing corridors through the data base for specific flight operations. This constrains the use of the data base for low altitude work to only a small part of the data base. It further restricts the flexibility of the data base and may provide negative cues when the pilot deviates from the corridor and notices a degradation in the density of visual cues. Third, reuse bits and pieces of the data base many times over to provide rich homogeneous scene content with the proper density of speed and altitude cues while restricting the actual number of polygons stored on the disk. It is this solution that will be discussed in detail.

In addition to physical storage requirements of the large gaming area data bas there is the issue of real time data base management by the image generator. Clearly, if the physical storage requirement were not solved, real time data base management would be an operator's nightmare of changing disk packs as the flight progressed throughout the data base. With large area data bases it is imperative that the data base be managed as efficiently as possible. The Evans & Sutherland CT5A data base is a hierarchical tree structure of geographically organized nested levels of detail. Embedded within the tree structure is information required to perform a variety of management and culling tests. This management and culling structure is processed by the IG hardware rather than by the general purpose computer. Since the structure is geographically organized, a particular eyepoint in the data base can be quickly traced in the data base tree and large parts of the tree eliminated through the culling tests[2]. A proper design of the top levels of the data base tree is essential to this process.

Another problem in the development of a visually rich large area data base is the availability of source material. Early projects in data base development relied heavily on airport blueprints, photos and pilot information. This works well for the airfield problem because of the limited scope of the project but presents difficulty for larger geographic areas. The large scale data base must rely heavily on aeronautical charts. Here, there is a lack of current and accurate information. It is not uncommon for charts to be as much as 10 to 20 years old. Further, as data base development includes areas other than the United States, availability of charts at the resolution required becomes a factor. A second source material problem is the gathering of terrain elevation data. Efficient extraction of contour data is time consuming and costly at best and for large data bases becomes so labor intensive as to make it impractical. The DLMS data base created by the DMA brings enhanced availability and accuracy of the contour data. Level I Digital Terrain Elevation Data (DTED) provides a grid of terrain elevation points at 3 minute intervals. Automatic processing of this elevation data provides a terrain model on which cultural features may then be added. The current cultural information provided by DMA through the Digital Feature Anaylsis Data (DFAD) is helpful but incomplete for visual systems since it was orginally developed for radar simulations. Only those features that have significant radar signatures are included in the data file. Until recently, significant navigable features, such as roads and railroads have been ommitted from the DFAD. The DMA is currently updating the DFAD data to a 2nd Edition specification which includes roads, railroads and other lines of communication[3]. Futher evolution in the development of source material by DMA is indicated in the High Resolution Prototype Specification[4] (HRPS). There is great potential in the use of this DMA data in semi-automation of the modeling process for large gaming area data bases.

'BITS AND PIECES'

Several problems have been identified with the development of high optical flow, scene rich, feature accurate, large gaming area data bases. The solution to all of these problems lie with some unique features of the image generator along with modeling tool strategies. It would be well to briefly review the CT5A system architecture and data base organization and structure for a complete understanding of the capabilities that are required to build data bases out of bits and pieces.

THE CT5A

The CT5A system is a pipeline of processing units where computing tasks are distributed along a sequence of dedicated computing elements. The front end of the pipeline consists of a viewpoint processor followed by a channel processor. It is the function of the viewpoint processor to perform an increasingly discriminating set of culling tests on the data base and provide the channel processor with a highly refined set of scene data that will eventually be displayed on the image plane. The very nature of the data base organization and structure allows the hardware to carefully manage and perform the culling tests necessary in the viewpoint processor[5]. The CT5A data base is a hierachical tree structure of geographically organized levels of detail. Within this structure is the data necessary to allow the viewpoint processor to relate the current eyepoint to paths in the tree structure. An additional feature of tree structure that supports the reuse of data base items in a general and extensive way is called instancing. A mesh or object in the data base tree structure may carry with it a positioning vector in three dimensions. This mesh or object and all subsequent data structure in the tree below it may be moved in real time to any location in the data base. This instancable structure may be referenced any number of times, each with a different translation. By cascading different levels of instanced meshes, extensive and complex data structures can be developed while only modeling and referencing a small collection of polygons. This allows a nearly total decoupling of memory requirements from apparent displayed scene densities[6]. For example, an object may be created to represent a simple tree as in figure 1. This object contains all of the scene elements necessary to represent that tree. Additional trees may be placed near this tree by referencing the first tree with different translations. This collection of three trees may be referenced four more times with offsets to create a 'forest' of 12 trees. These virtual memory models of the dozen trees all reference a single collection of polygons that were used to model the original tree.

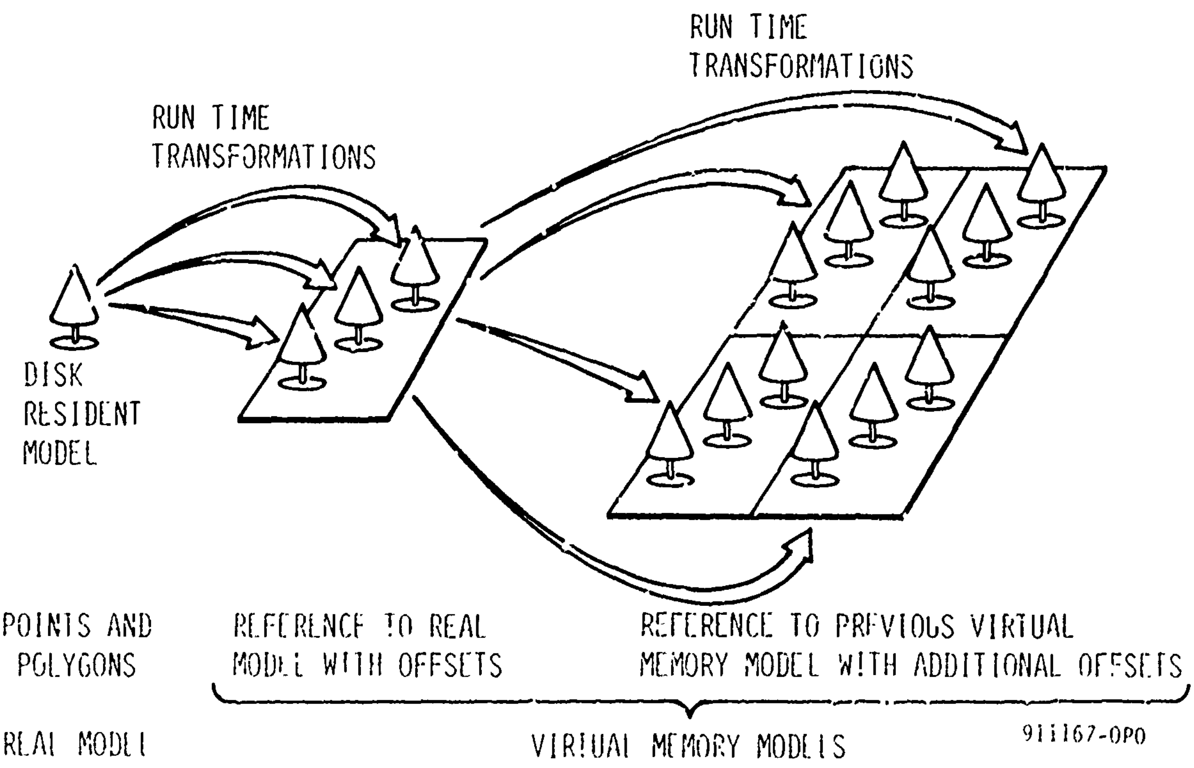

Figure 1: Instancing

MANUFACTURE THE DATA BASE OUT OF GENERIC PIECES

Extensive use of instancing is made in relieving two of the concerns with the development of large gaming area data bases. First, cost of the data base is lower due to significant reductions in the total number of surfaces modeled and semi-automation of the modeling process. Second, the amount of physical storage required is reduced to one or two disk packs, while at the same time scene densities and high optical flow are homogeneous throughout the data base. Homogenous scene densities of 2,000 polygons per square nautical mile for a 70,000 sq. n.m. data base have been achieved using only one RP06 disk pack.

The Component Library

One of the most important features of large gaming area data base development is the choice and creation of a comprehensive component library, suitable to the area being modeled. A component library is a generic collection of those cultural features that are normally found in the geographic area being modeled. For example, in the coastal mid-Atlantic states, one would expect to see farm complexes, schools, churches, drive in theatres, strip mines, power plants, and shopping centers. An extensive list of cultural features can be compiled by reviewing photos, charts and other source data from the geographic area considered. The Defense Mapping Agency has completed its own list of cultural features in its DFAD specification and the specification for High Resolution/Terrain Analysis Applications. These feature identification definitions are broken down into general categories such as Industry, Transportation, Commercial/Residential, and Commercial/Recreational. Each of theses categories is further subdivided into specfic features. For example, the Commercial/Recreational category contains features where the major business activities and recreational facilities of an urban area are conducted. Features listed in this category include such things as water slides, roller coasters, advertising billboards, overhead highway signs, and drive in theatre screens. If several models of each of the cultural features in the component library were created, each with a different orientation and color, a large collection of generic real world cultural features would exist for the data base. Aids to the development of these models are also included in the appendix to the DMA product specifications. Drawings of specific features, such as roof types, tower types, and bridge types, are part of the DMA product specifications. Once a comprehensive feature library has been developed, these models may be placed liberally throughout the data base in places appropriate to the individual feature. A single model of a farm house might be used 200 times while a drive in theatre may be only be used 20 times. An entire data base may be built using only cultural features from the component library. Since the component library is modeled with a few orientations for each feature, significant savings in data base designer time and off-line computer resources are realized.

The Basis Set

The notion of a basis set is an extension of the concepts used in the component library. The basis set is a carefully designed set of components that are used frequently in the data base. Their use is so frequent that the basis set tends to assume a semi-permanent residence in the environmental memory of the CT5A, thus reducing disk access. The basis set may consist of a set of road segments, that when placed end to end form a stylized road that closely appoximates a map correlatable road on a navigation chart. For example, a set of interstate road segments may be modeled 2,000 meters long at 15 degree heading intervals. If an

approximate error of 260 meters in the end point of the road is acceptable, all of the interstate highways in the data base may be represented by a set of 12 road segments. Each road segment may include automobiles, trucks, centerline stripes and other enriching features that are not necessary for navigation but add to the optical flow of the data base. The basis set may also include a collection of coastline shapes that when pieced together form an actual representation of a particular section of coast. The same applies to large areas of forest, desert or swampland. The greatest leverage, however, is gained when the basis set is used to represent sections of terrain. If terrain elevations throughout the data base were represented on a regular rectilinear grid, then the entire data base could be 'skinned' by a collection of regular right triangles as shown in figure 2. Secondly, if each grid point were adjusted or 'filtered' to a specified tolerance, say the nearest 100 foot interval, then we would have a grid of regular right triangles whose vertices are a multiple of 100 feet. This implies that there exists a finite set of regular right triangles that match the triangles in the terrain grid. Therefore, a collection, or basis set of regular right triangles can be modeled to suit the general topography of the area being modeled. Each triangle may include such things as trees, rocks, bushes and areas of 2D texture. Once this finite set of triangles is modeled, they may be instanced into the triangular grid to represent a stylized version of the terrain with a very high density of optical cues. This strategy makes it possible to model very large areas of terrain with comparatively few actual polygons.

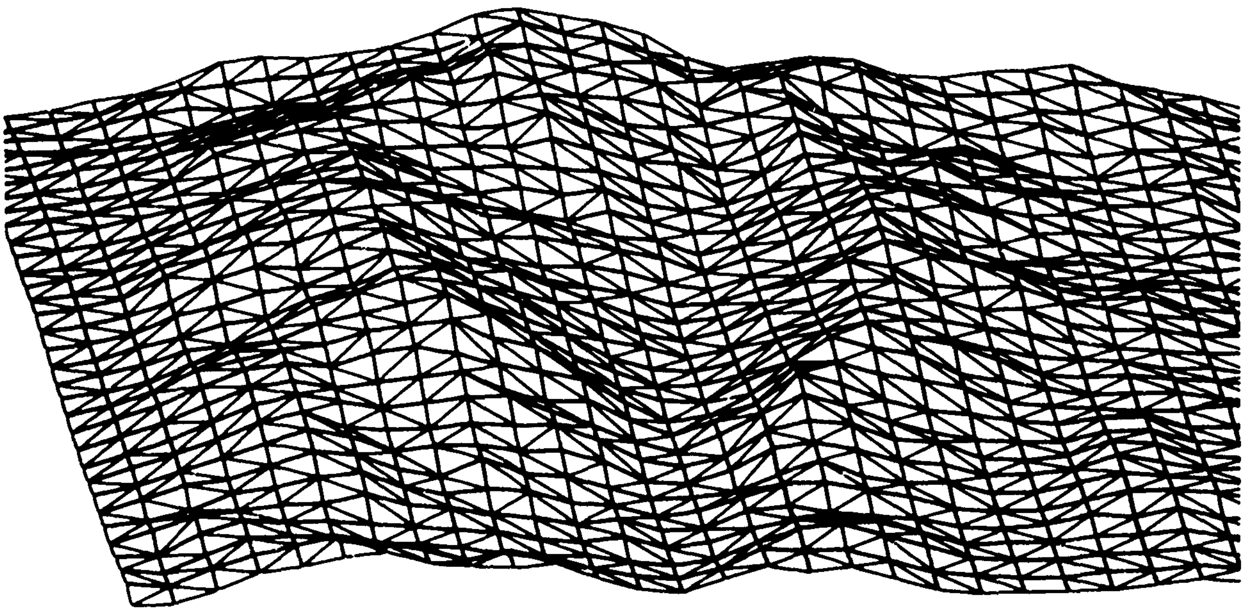

Figure 2: Right Triangle Fitting

Further, the modeling effort can be significantly reduced by using automatic terrain production procedures from standard digital format terrain data tapes. The DLMS, produced by the DMA, contains DTED that meets the requirements for the regular grid specified above. For a given geographic area, these tapes are read, filtered as necessary and then fit with a specific terrain triangle from the basis

set, all without modeler intervention. The modeler then adds cultural features in areas desired. This addition of cultural features may be semi-automated through the development of interactive graphical tools to complete the modeling exercise.

THE GRAPHICS WORKSTATION

Data base development costs and terrain fidelity/complexity are two of the foremost concerns in the construction of a large geographic area data base. Ideally, the data base development process should be fully automated. However, sufficient source data in the form of digital tapes is simply not available. A semi-automated data base production tool is required that uses a combination of available source material. Such source material may be DMA DTED and DFAD tapes, aeronautical charts or photos. This source material should be accessed in a fashion that is not labor intensive. An Evans & Sutherland PS330 interactive graphics workstation is used to present a stylized view of the data base as it is constructed. In an effort to reduce mainframe computer costs, the optimization of the host computer's communication with the workstation is of prime importance in making use of available computing resources. The interactive process must take place in a distributed graphics processing environment. Distributed graphics allow the host program to partition an application into graphical and non-graphical portions and to distribute the graphical portion of the task to the graphics workstation, thus causing communications with the host to take place at a relatively low bandwidth. As a result of the lower bandwidth, it is possible to communicate with the host using standard equipment and protocols. The graphics workstation can in fact look very much like a standard terminal on the mainframe. In the distributed graphics environment real time rotation and scaling of displayed objects can take place without host interaction. Additionally, data structures may be created, incrementally modified and deleted at the direction of the host computer without the need to retransmit the entire model. Mass memory in the workstation is available such that very large data structures may exist in the graphic display's memory, again reducing retransmission time from the host. Interactive devices attached to the workstation include keyboard, data tablet and stylus, control dials and interactively labeled function buttons.

The Terrain Square Editor

The Terrain Square Editor (TSE) is a software tool based on the PS330 that allows the data base designer to interactively place features from the component library onto a terrain model.

The Terrain Model

The geographic area that is used for modeling is related to the top level design of the data base tree. Standard design for most of the large gaming area data bases have led to the use of the Universal Transverse Mercator (UTM) grid as the selected projection for data base modeling. This projection allows the use of terrain squares that are either 10,000 or 20,000 meters on an edge. If DMA DTED source material is used for building a terrain model, a preprocessor uses that information to build a terrain model for the specific terrain square. This preprocessor corrects the DMA data to UTM coordinates, filters the data, matches edge conditions and automatically creates a terrain model to specifications and tolerances selected by the data base designer. This terrain model is then passed to the PS330 and is represented graphically by a wire frame model as shown in figure 2 above. This model may be scaled and rotated interactively for viewing from any eyepoint. Selection of a basis set to represent various terrain types is also accomplished here.

Terrain Enhancement

Once the terrain model is complete and displayed on the PS330 the data base designer may enhance the terrain with cultural features. A number of sources may be used with the terrain square editor. The primary source is the data base designer, who, with a knowledge of mission requirements and image generator constraints, adds cultural features to the terrain from the component library or basis set. Aids to the placement of the cultural features come primarily from aeronautical charts that are placed on the digitizing tablet. Using a stylus the designer is able select features from the component library and accurately place them into the data base with the aeronautical chart as a guide.

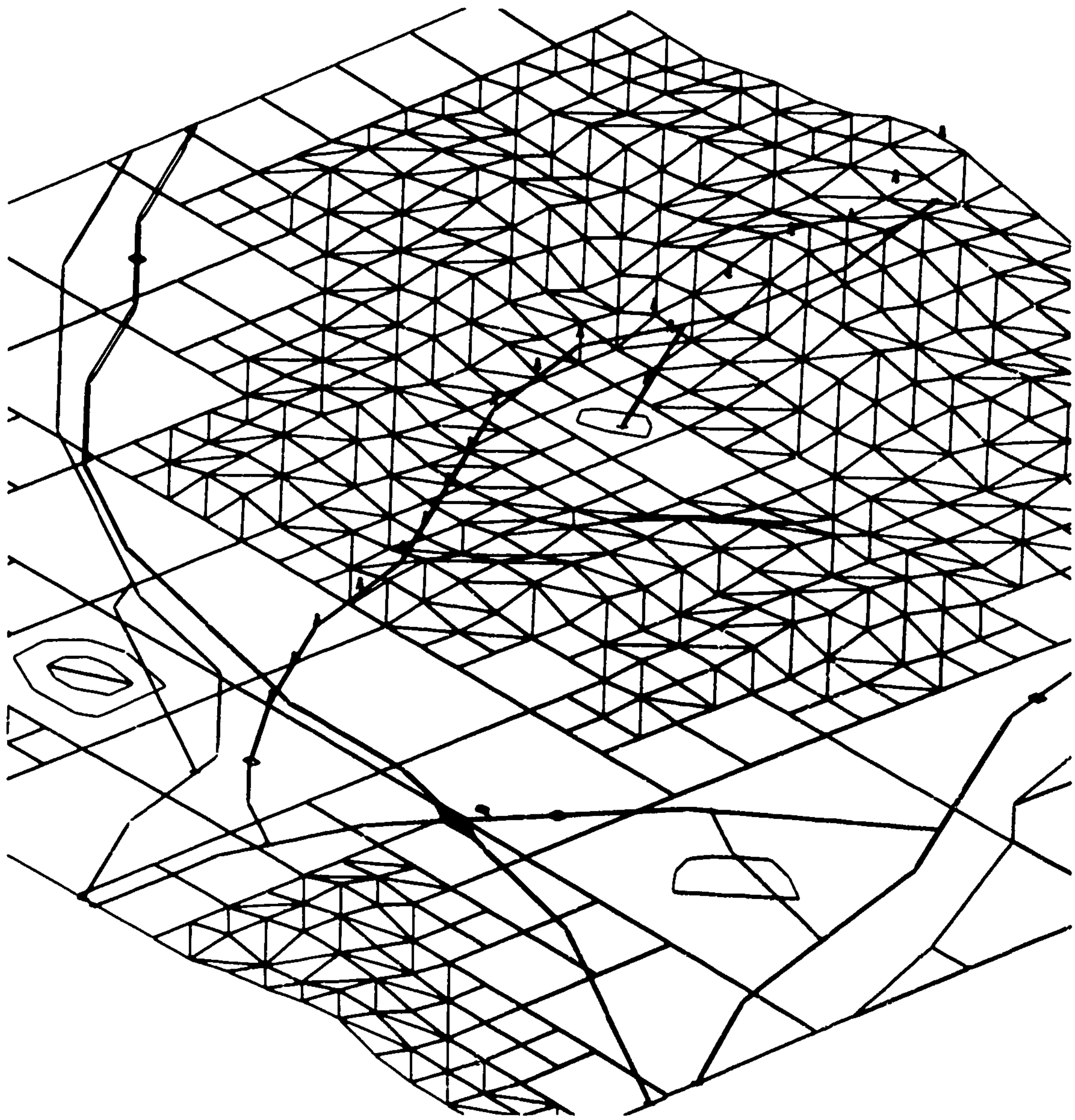

Figure 3: Terrain Model With Added Cultural Features

A future implementation will use DMA DFAD data as a direct overlay on the PS330 screen and the designer will be able to pick features that appear in the DFAD data. Since the DFAD data is incomplete it may be supplemented with choices from the library based on the aeronautical chart on the digitizing tablet. This approach has several advantages. First, since the component library was developed from the feature descriptors in the DMA DFAD product specification, models of all the features displayed will be available. Second, problems of misregistration will be eliminated because of the graphical feedback immediately available to the designer through the PS330 screen. Misregistration occurs when a combination of source material is used as in this case. For example, a bridge might be placed in the data base from the DMA DFAD data, while the river underneath the bridge is placed using the aeronautical chart. The end result may be that the bridge is 200 meters away from the river. Since the graphics program is interactive and immediate feedback is available, the stylus may be used to select the bridge and 'drag' it into its proper position over the river. Each of the models in the component library have a simple PS330 representation that represents the "footprint" of that feature projected onto the X-Y plane. These footprints aid the modeler in accurately placing features on the terrain. It ensures that features do not overlap each other or are placed in unusual locations. Figure 3 shows a partially completed terrain square with roads, highway interchanges, transmission towers and footprints of several cultural features that have been added to a terrain model.

Each model also has associated with it a precomputed IG load factor. This load factor is calculated as the library model is developed and can be related specifically to the individual configuration of the image generator. As the models are added to the terrain square the IG load factor is displayed. The designer may then continue to add models to the terrain square until the design system load for the particular IG configuration is reached. When IG load becomes a significant factor, the 'man in the loop' is essential in determining which features are necessary for the best scene content. The strategy involved is to first place all features which are navigationally significant and then add additional features until the load limit of the image generator is reached.

The Postprocessor

Data from the terrain square editing process is written to an intermediate file. This intermediate data file is processed off-line and a CT5A compatible data file is written, compiled and linked into the run time visual data base. The use of an intermediate file structure has a distinct advantage for sensor correlation. Historically, data bases for additional sensors such as digital radar, infrared sensors, and synthetic aperture radar have been constructed independently of the visual data base. This results in duplicate data base development costs and more importantly, lack of correlation between the 'out the window' visual scene and the sensor displays. Writing the results of the terrain editing process to an intermediate file format allows the development of additional postprocessors that would automatically generate on-line data bases for the entire sensor suite. These data bases would share the development costs of the visual data base as well as ensure correlation between the visual displays and the sensors. Figure 4 below shows the complete flow of the modeling process.

Automation

The concept of a component library and applying offsets to these features parallels notions developed by DMA for the DLMS DFAD and the prototype specification for Level V and Level X. As the specification becomes formalized and DMA commits to

production of Level V data bases the terrain editing process may move closer to full automation. There remain many problems to be solved with regard to IG load and capacities, but in the time frame given for full production of Level V data bases we expect significant additional increases in IG capabilities.

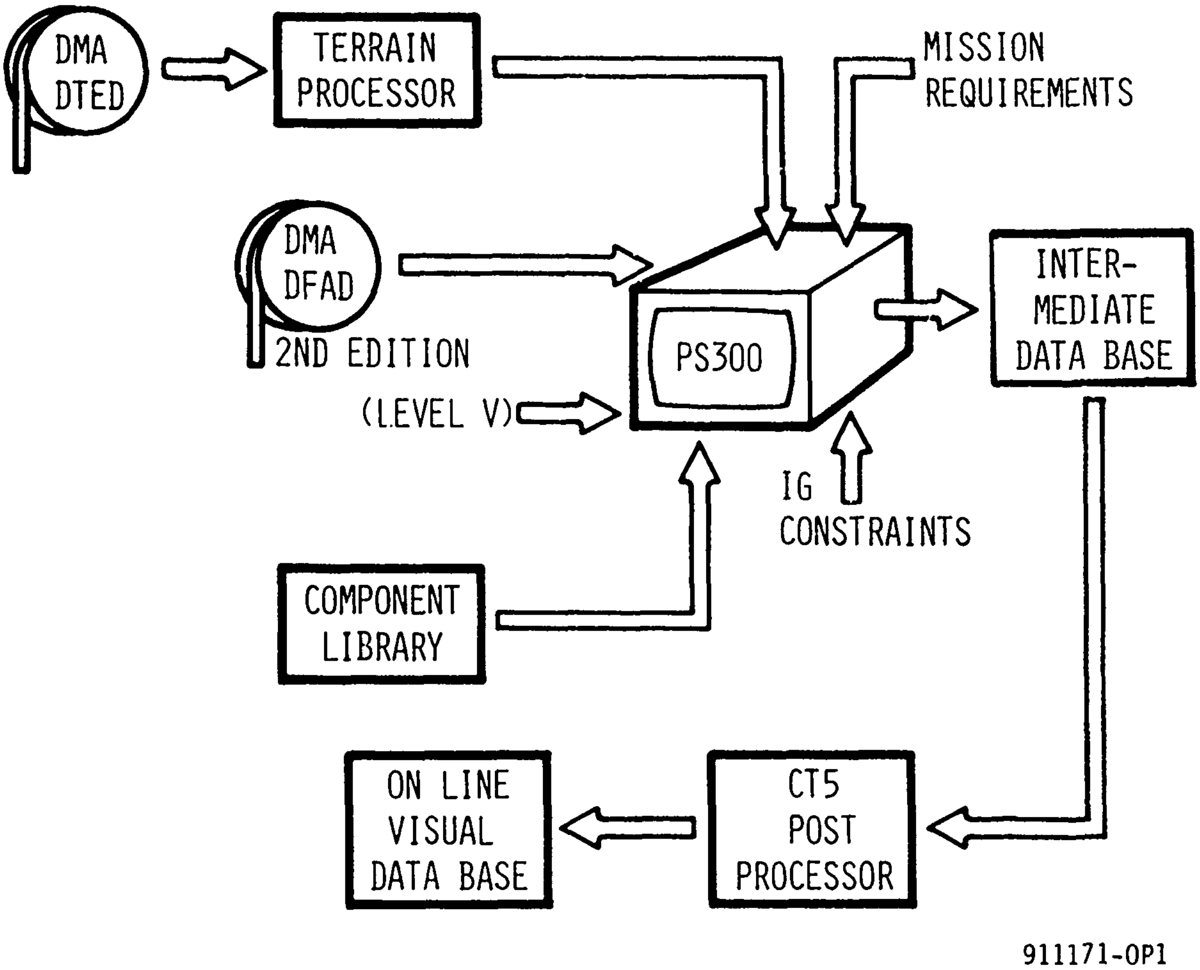

Figure 4: Modeling Process

CONCLUSIONS

Significant problems exist in the development of large gaming area data bases that exhibit rich homogeneous scene detail. Data base development costs are high, data base on-line storage requirements are massive, real time data base management may be difficult, source material availabilty and reliability are questionable and sensor correlation is sometimes not achieved. These problems are addressed through the development of data bases using 'bits and pieces'. Interactive data base development using terrain models from DMA DTED, a component library and a basis set solves these problems with a bit of help from the CT5A instancing capabilities. The future points to more and more automation in the development of the data bases through the use of increased capabilities in the image generators and a comprehensive visual data base from DMA. One factor will never be left out of the development of data bases, however, and that is the opinions and desires of the pilots who fly the machines. They ultimately determine the content and acceptability of any data base.

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THE GENERATION OF THREE-DIMENSIONAL DATA BASES USING A BUILDING BLOCK APPROACH

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THE GENERATION OF THREE-DIMENSIONAL DATA BASES USING A BUILDING BLOCK APPROACH

ABSTRACT

Simulation system visual data base designs must provide engineers and test pilots with adequate realism in mission scenarios to insure acceptable results without the luxury of long design schedules. The objective is to build large three-dimensional data bases quickly and efficiently, while generally matching terrain and landscape features. The BUILDING BLOCK approach is presented as a means to achieve this objective. An example is presented to illustrate this approach.

INTRODUCTION

In an effort to resolve economically the engineering demands, requirements, and complexities of today's sophisticated aircraft, General Dynamics has embarked on an orderly simulation growth plan. A portion of that plan involves simulation research and development in out-the-window and in-the-cockpit sensor visual display flight simulator systems.

As aircraft systems become more complex, simulation efforts must be increased. As simulation efforts propagate, the requirements and complexities of the visual data bases expand dramatically. The objective, or goal, then is to design a visual data base that provides the engineer and test pilot with adequate realism within a reasonable time frame and also produces a synergism between the visual scene, aircraft sensors, and customer or user requirements. In this paper, the BUILDING BLOCK approach will be discussed as one way of satisfying specific user requirements.

THE BUILDING BLOCK APPROACH

Any simulation system's visual data base design must meet the challenge of increased capacity presented by today's Computer Generating Image Systems. Additionally, it must satisfy user demands, provide adequate realism for the engineers and test pilots, yet stay within the constraints of the visual system's hardware/software architecture. User requirements will vary depending on the type of simulation program established. As the requirements become more complex, the difficulties of creating the visual data bases will increase.

The complexities of the missions contained within the visual data base will dictate how many scenarios will be required. Each scenario requires that certain visual cues be present to insure that the proper stimuli are presented to simulate more effectively the real world situation and assure user acceptance. One method of increasing specified terrain density, enriching scene content, and satisfying simulation requirements is through the use of BUILDING BLOCKS. In addition, this method accords faster turn-around times when creating different terrain flight profiles.

The specifics of today's visual terrain data bases are sometimes derived from map details. Attempts to match specific terrain details on a one-to-one basis with maps is quite a tedious and time-consuming task. Manpower requirements are enormous per unit of terrain area created. In the BUILDING BLOCK approach, manpower needs are vastly reduced because only a small unit of terrain area needs to be modeled. The BUILDING BLOCK approach can create visual scenes generically to resemble any man-made or natural topographical feature. This can be accomplished by carefully "disassembling" the required feature into its basic parts or pieces. From these pieces, generic parts are created. By careful rearrangement and assembly, these same parts can be made to resemble several different features or give different appearances to the same feature. Using this BUILDING BLOCK approach, a residential area can be built from the pieces of one "house". The pieces that make up the residential area can be combined to build entire cities (Figure-1). This method could be used to generate one mountain, or a complete range of mountains. By composing selected blocks in a carefully orchestrated theme, scenario needs are fulfilled, and the most exacting and stringent user requirements can be satisfied quickly and economically.

TERRAIN FOLLOWING MISSION REQUIREMENT EXAMPLE

In simulating a flight for today's high performance aircraft, the visual requirements may contain a variety of distinct design goals. While each goal may be viewed independently, priorities should be established for the more important ones. One of the essential goals is to design missions to flight test the aircraft's responses to its onboard computers, sensors, and other related avionic equipment. These devices help to control the flight path of the aircraft and aid the pilot in responding to the real-world terrain.

Because the real-world terrain is so variable, the test pilot must be able to fly several preplanned courses over an extremely large area in order that the visual, analytical, and aircraft responses may be thoroughly evaluated. Following these runs, the aircraft's performance coupled with the programmed data can be measured and any necessary corrective action taken.

Creating realistic terrain, utilizing several different profiles (Figure-2) covering a large area of the earth, and testing an aircraft's capabilities and responses to its own avionic equipment are very important design goals.

In the BUILDING BLOCK approach of designing a visual terrain data base, an elevation map of the desired representative geographical area is obtained (Figure-3). The profile is developed either by over-flying the area and recording the elevations, or describing a track across the map's surface and plotting the elevations (Figure-4). This profile curve is closely scrutinized, manageable sections are established (Figure-5), and a zero base line is selected (Figure-6).

The BUILDING BLOCK approach views the earth as flat. This makes the generation of the visual data base much easier and faster because the host computer is used to manipulate the elevation changes and curvature of the earth variables that put the data back into its proper shape.

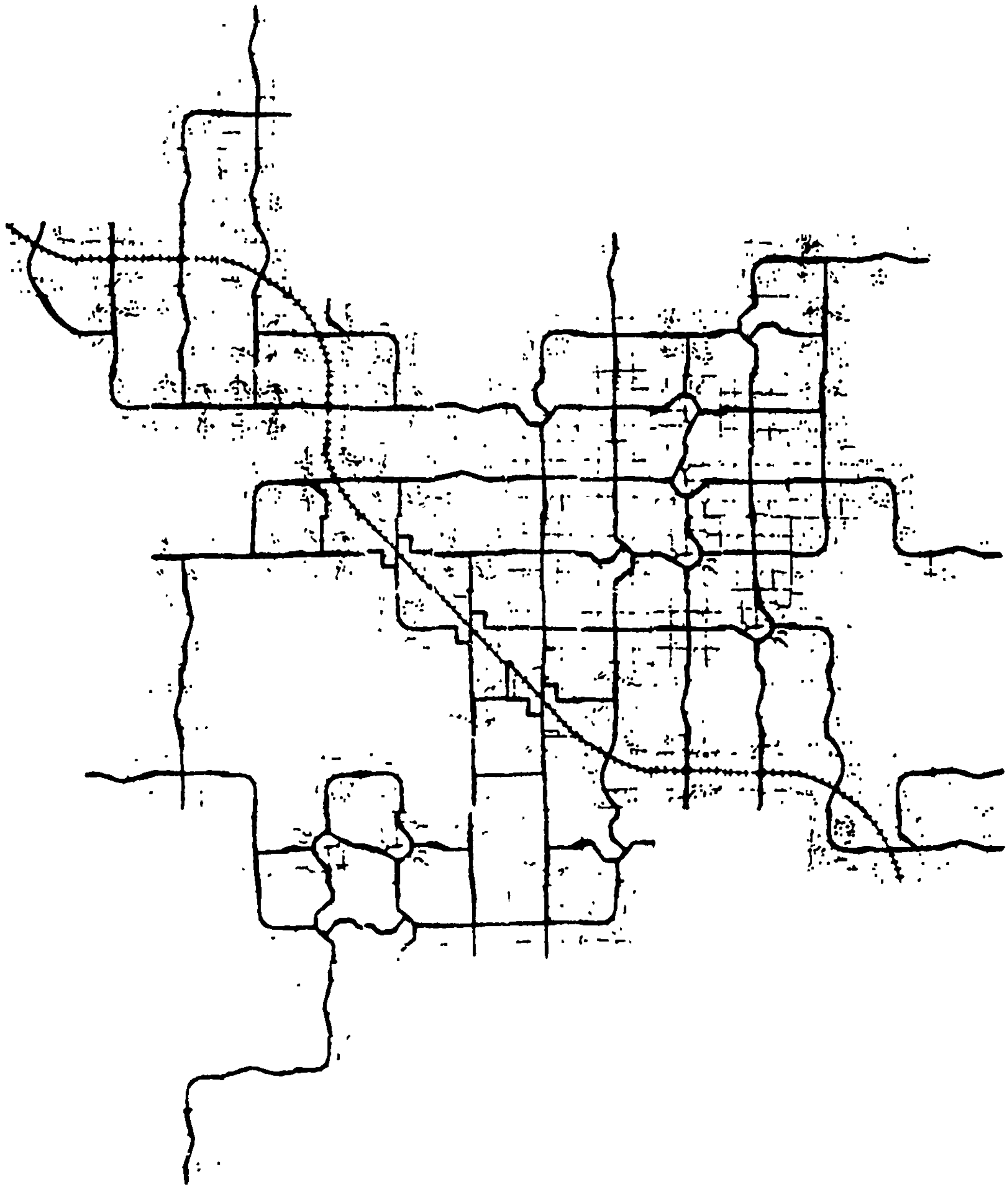

FIGURE 1. GENERIC CITY

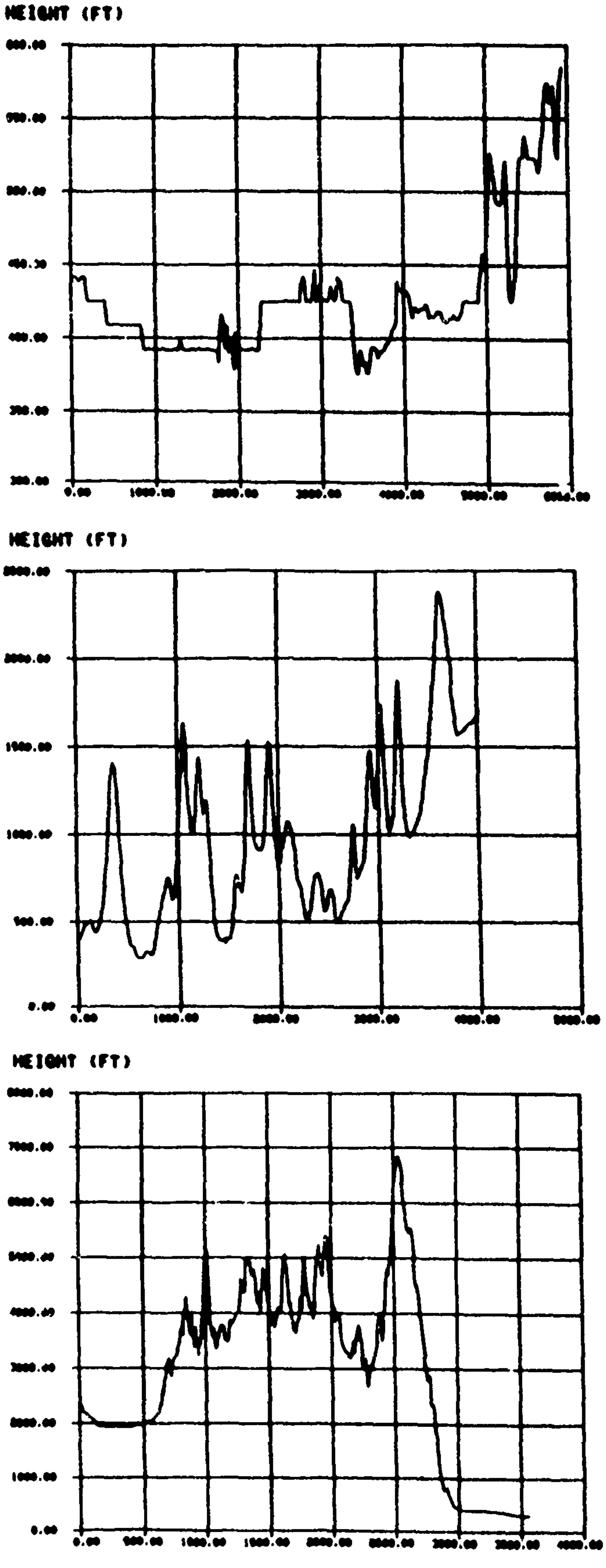

FIGURE 2. TERRAIN PROFILE DATA

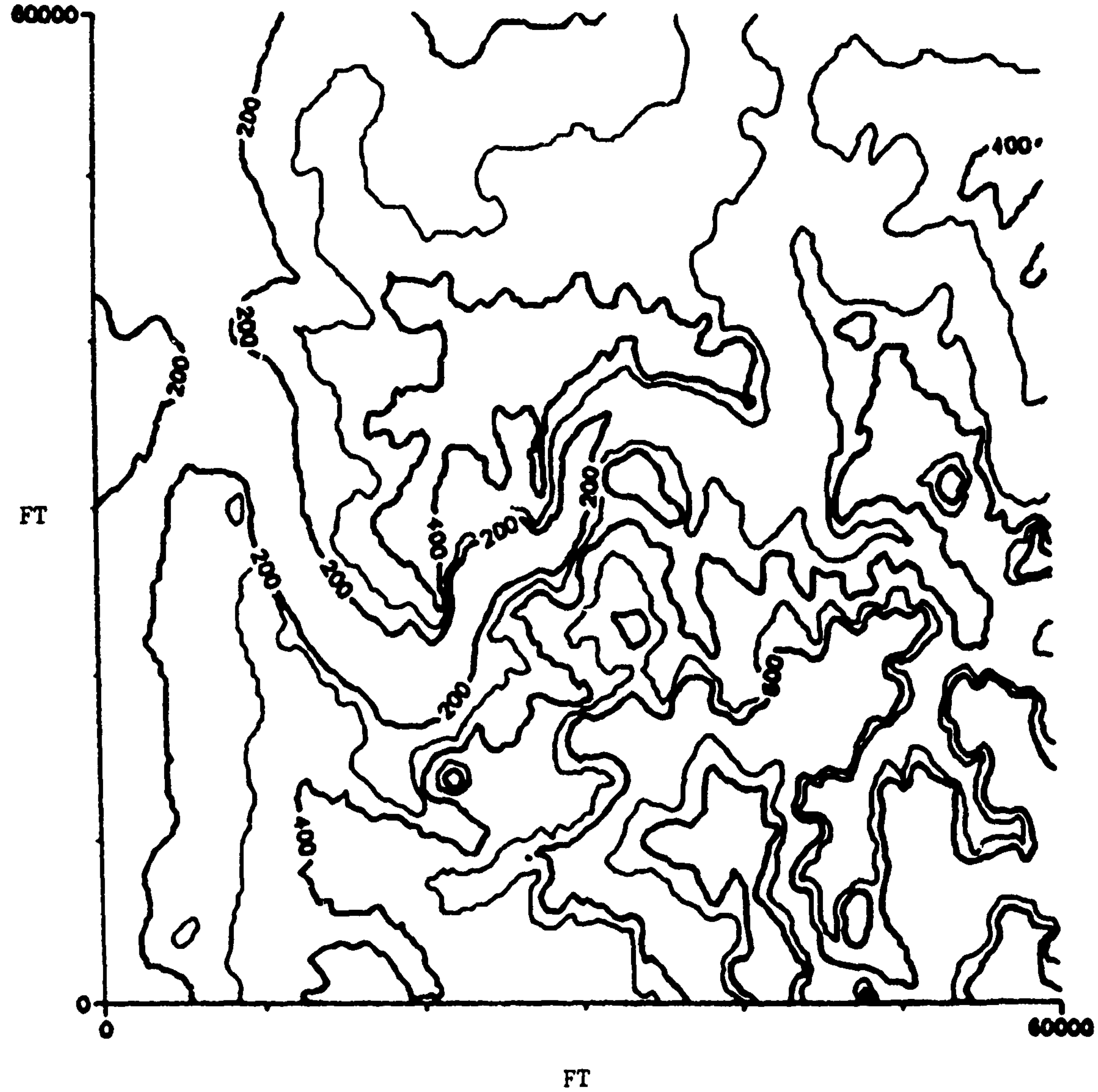

FIGURE 3. TERRAIN ELEVATION MAP

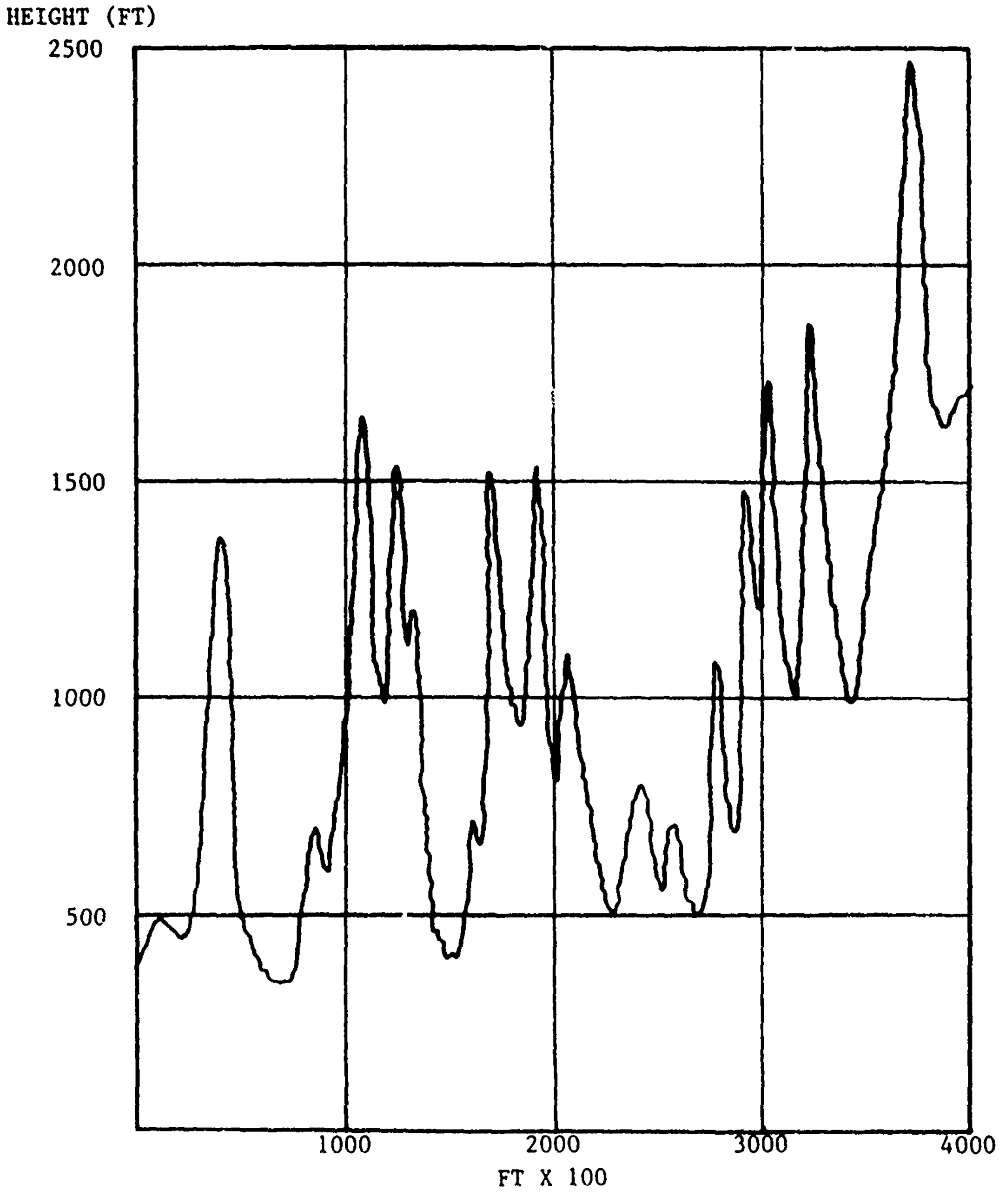

FIGURE 4. DESIRED TERRAIN PROFILE

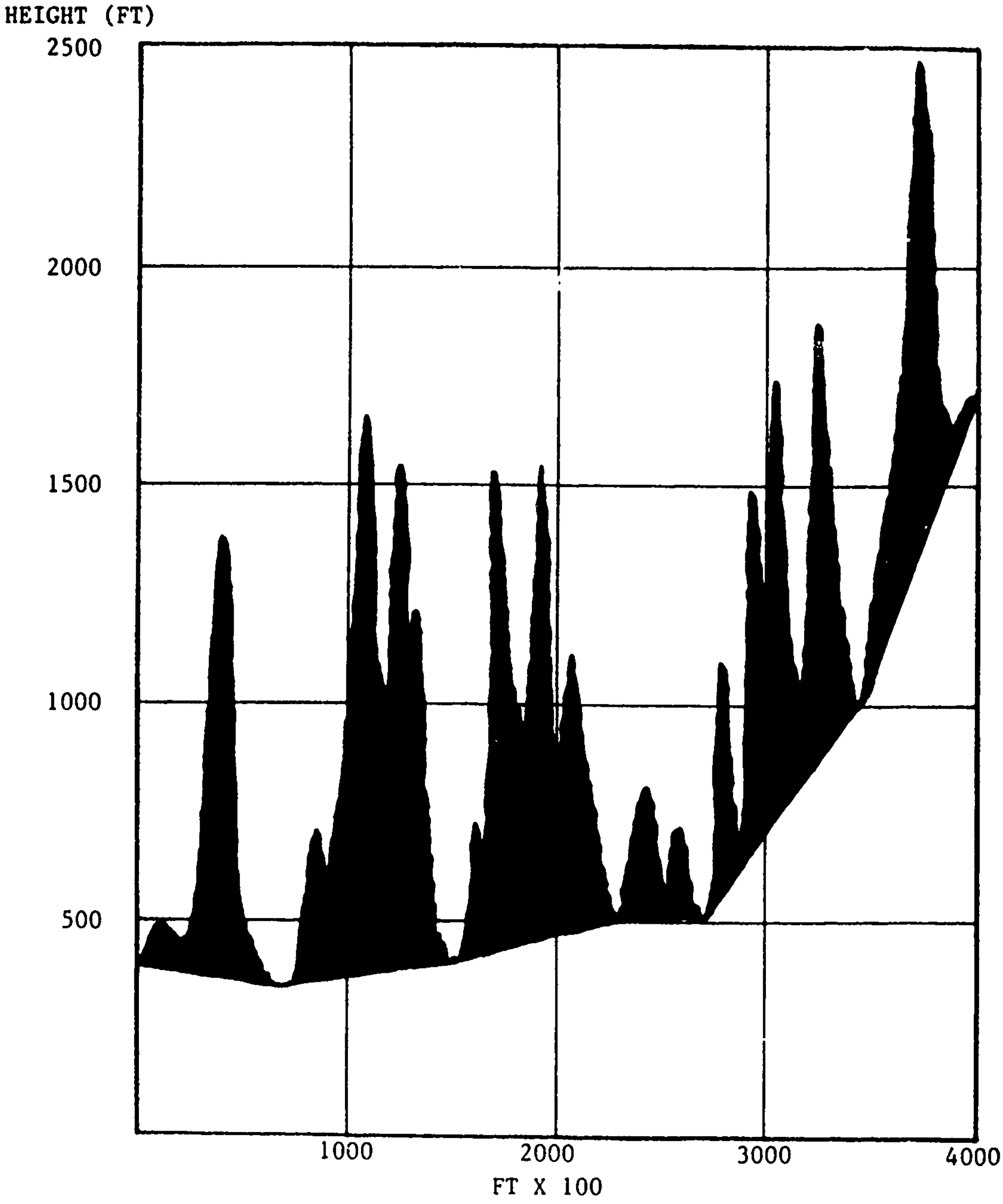

FIGURE 5. SECTIONING TERRAIN DATA

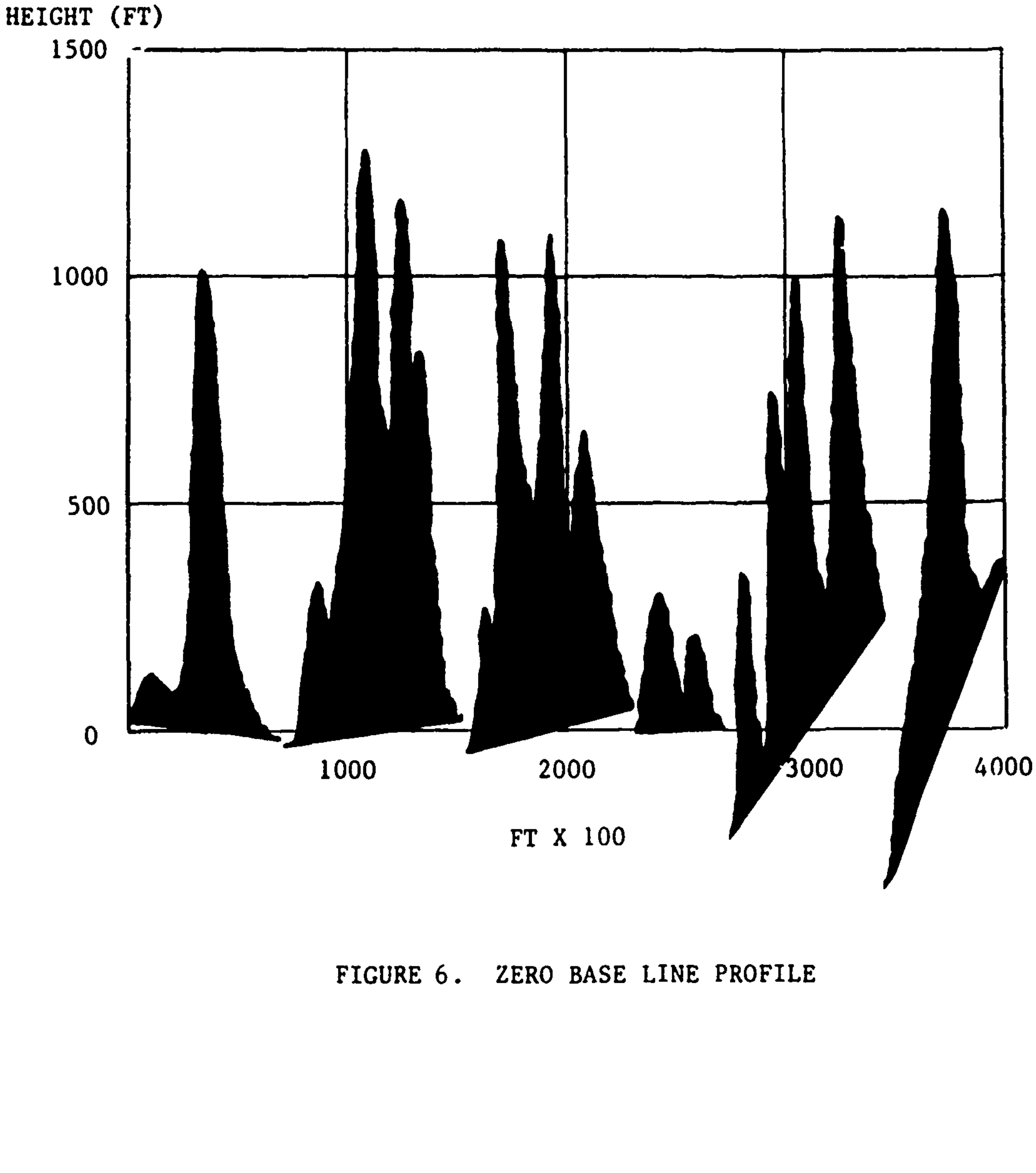

FIGURE 6. ZERO BASE LINE PROFILE

The highest elevation in this profile is determined to be 1300 feet above the zero base line with the average elevation being about 400 feet. One building block, with variable height adjustments, is created for the elevations between 400 and 1300 feet. Three building blocks are made for the elevations between zero and 400 feet. A flat building block is developed for the small elevation variances between the higher hills. Only five building blocks are necessary to approximate this entire terrain profile curve (Figure-7).

A general panorama of hills and valleys is developed, and embellishments are added (Figure-8) to create the type of visual phenomena necessary to sustain height-above-terrain cues consistent with the constraints of the visual system.

By making small changes in the variables and interchanging the building block material, dramatic changes can be made in the visual data base. Thus, new and distinctive profiles may be created, and any familiarity with a flight path can be eliminated.

SUMMARY AND CONCLUSION

In building any large three-dimensional terrain visual data base, the objective is to build it quickly, efficiently, and at the same time keep the terrain and landscape features as real as possible. This objective can be realized using the BUILDING BLOCK approach. It allows more time for the data base scientist to create visual cues and reduces manpower requirements. Since there is only a small amount of unique data present, real-time correlation between onboard instrumentation and the visual terrain is possible. However, its greatest advantage is that the technology is transferrable to any system in use today because it is not hardware dependent.

REFERENCES

Smart D.D. and Chirieleison A.C., "The Design of Computer Generated Images. The Research and Engineering Simulation Laboratory Problem. It's More Than What Meets the Eye", AIAA 22nd Aerospace Sciences Meeting, Paper No. AIAA-84-0556, January 1984, Reno, Nevada.

ACKNOWLEDGEMENTS

We wish to thank Capt. A.B. Crimmins, a Service Representative to General Dynamics, for his support in editing this paper.

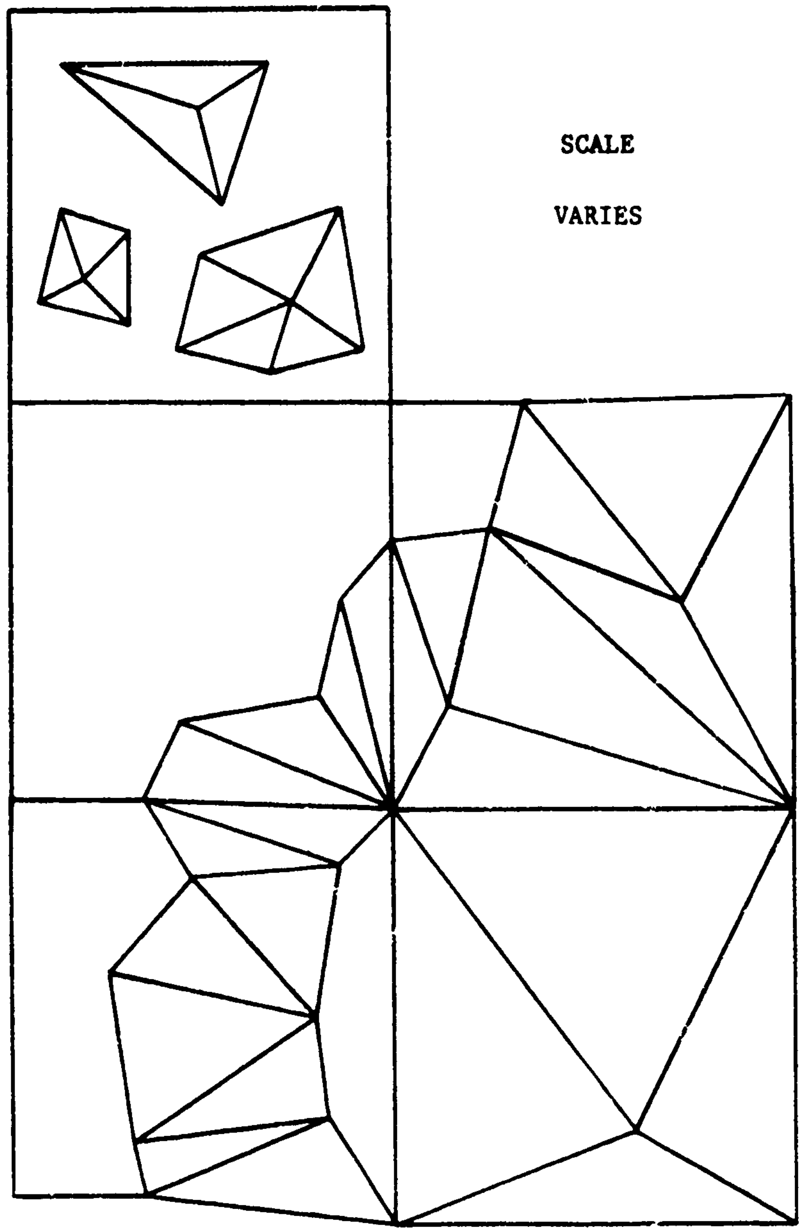

FIGURE 7. BUILDING BLOCK PIECES

FIGURE 8. EMBELLISHED PANORAMIC BUILDING BLOCK SCENE.
(Embellishments By Michael Jackson)

Luspie

DATA BASE GENERATION SYSTEM FOR COMPUTER GENERATED IMAGES AND DIGITAL RADAR LANDMASS SIMULATION SYSTEMS

By Lt. Col. Manfred Haas, Diether Elflein and Peter Güldenpfennig

ABSTRACT

The paper deals with a semi-automatic, interactive system to generate data bases from Digital Landmass System (DLMS) Data, for Computer Generated/Image Visual Systems (CGIVS) and for Digital Radar Landmass Simulation (DRLMS) Systems.

Terrain information and certain culture features can be gained from DLMS data automatically for CGIVS and DRLMS data bases. Additional information is prepared by interactive methods, including the use of model library for CGI data bases developed by batch procedures. Data bases can also be developed solely by batch procedures.

INTRODUCTION

In 1975 the German Airforce and Navy decided to use a Computer Generated Image Visual System (CGIVS) and a Digital Radar Landmass Simulation (DRLMS) System for the TORNADO Operational Flight Training and Tactics Simulator.

The development of the prototype CGIVS demonstrated that in order to fulfill the operational requirements for this type of simulator, a substantial increase in scene content would be necessary. Therefore, the CGIVS production units have a much higher data processing capability than the prototype. Table 1 shows a comparison of the capabilities of the prototype CGIVS and production units.

INTRODUCTION (Cont.)

The increased scene content for the new CGIVS had substantial impact on data base generation. For the prototype system, the CGIVS data bases had been generated manually by batch operation. The areas and models had been derived from geodatic charts, areal photographs, blue prints, and normal photographs. The scene content of this material was reduced and manually transformed into graphic vectors. The coordinates of the vertices of the edges were defined on punched cards. Only after the coordinates of the vertices had been defined on the punched cards automatic data processing could be used for operations such as reading-in, testing, scaling and computing of face normals and separation planes.

The high information density of the data bases for the new CGIVS led to the necessity for use of automatic and interactive procedures for the development of data bases. For this new CGIVS, Messerschmitt-Bölkow-Blohm (MBB) , designed the Data Base Generation System (DBGS). This DBGS will not only be used for the design of data bases for CGIVS, it will also perform generation and modification of data bases for the DRLMS system. It is worth mentioning that all DRLMS for the German and Italian TORNADO simulators have an up-date console with which small modifications to the data bases can be performed. One system out of the six ordered by the German Government and one of the Italian Airforce systems has additional computer peripherals used to transform source material into online data bases. The source material for this transformation program is cartographic information in digital form in accordance with the product specification for Digital Landmass System (DLMS) Data Base/ICD/100 1. Edition, July 1977.

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DEVELOPMENT OF VISUAL DIGITAL DATA BASES

Structure of the Visual Data Bases

The data base for the CGIVS represents the mathematical description of the stylized world. This description is in coded form on a storage medium, so that the CGIVS can read it out in an online process and can perform further data processing tasks.

The geometry of the "world" is defined by points, lines and faces. A point is defined by storage of its X-, Y-, and Z-coordinates. Two points define a line. By the use of several lines a closed polygon can be developed which represents a face. The CGIVS shows points and faces which are described not only by their geometrical position, but by other attributes like color, texturing, or curved surface shading.

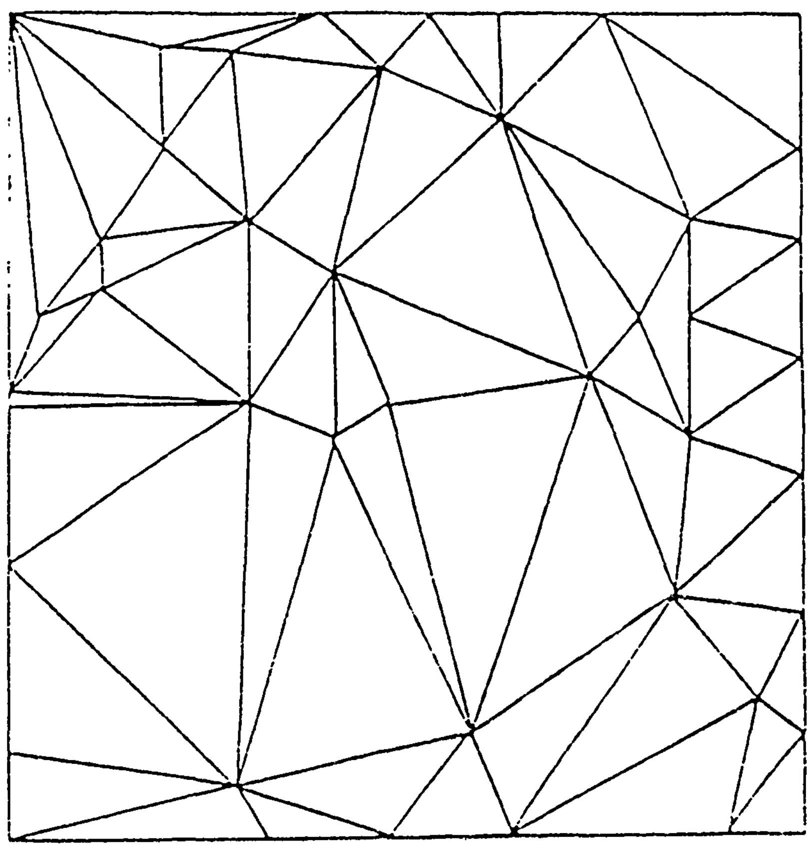

Figure 1: Terrain Approximation

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The morphology of the terrain is approximated by triangles (see figure 1.). Outlines and position of the triangles are matched to the terrain in an optimum manner. The number of triangles, and therefore the information density of the data base, is a function of the roughness of the terrain. This means that the information density of a planar landscape is relatively small, and for mountainous terrain, it is very large.

It is possible to divide these triangles into more faces, in order to show changes of ground vegetation and culture features by means of different attributes.

Three-dimensional objects can be built out of these faces. These objects, in turn, form more complex models. Objects are always convex, while models can also have a concave character. Objects and models can represent houses, towers, bridges, etc., which are positioned in the terrain.

In principle the DBGS enables three methods of data base generation: Automatic transformation, interaction and batch (see figure 2.)

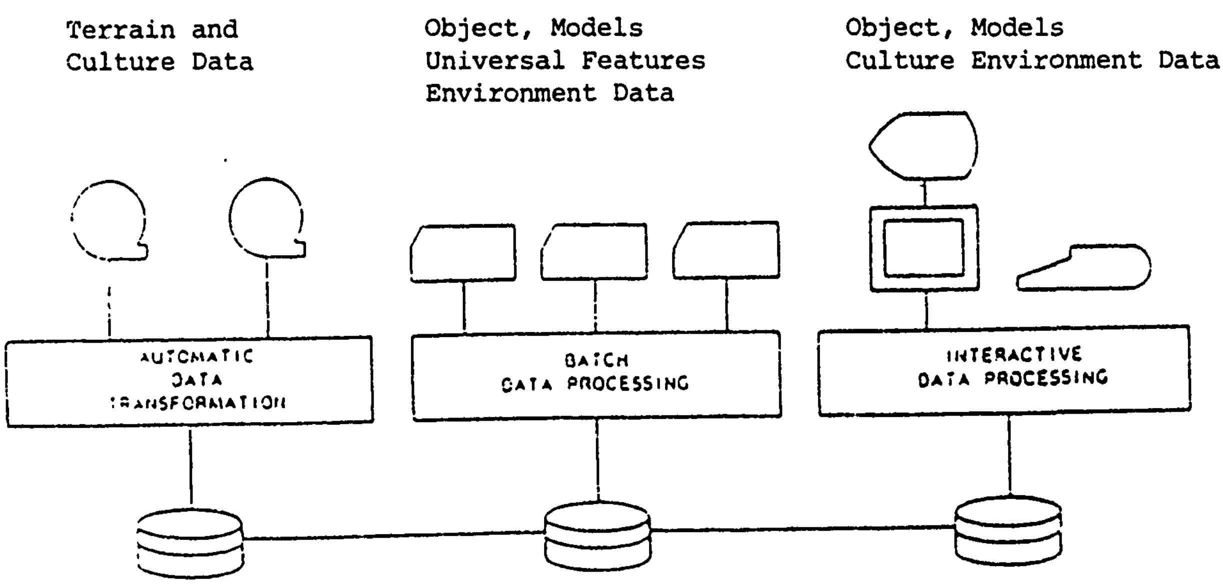

Figure 2: Data Base Generation System

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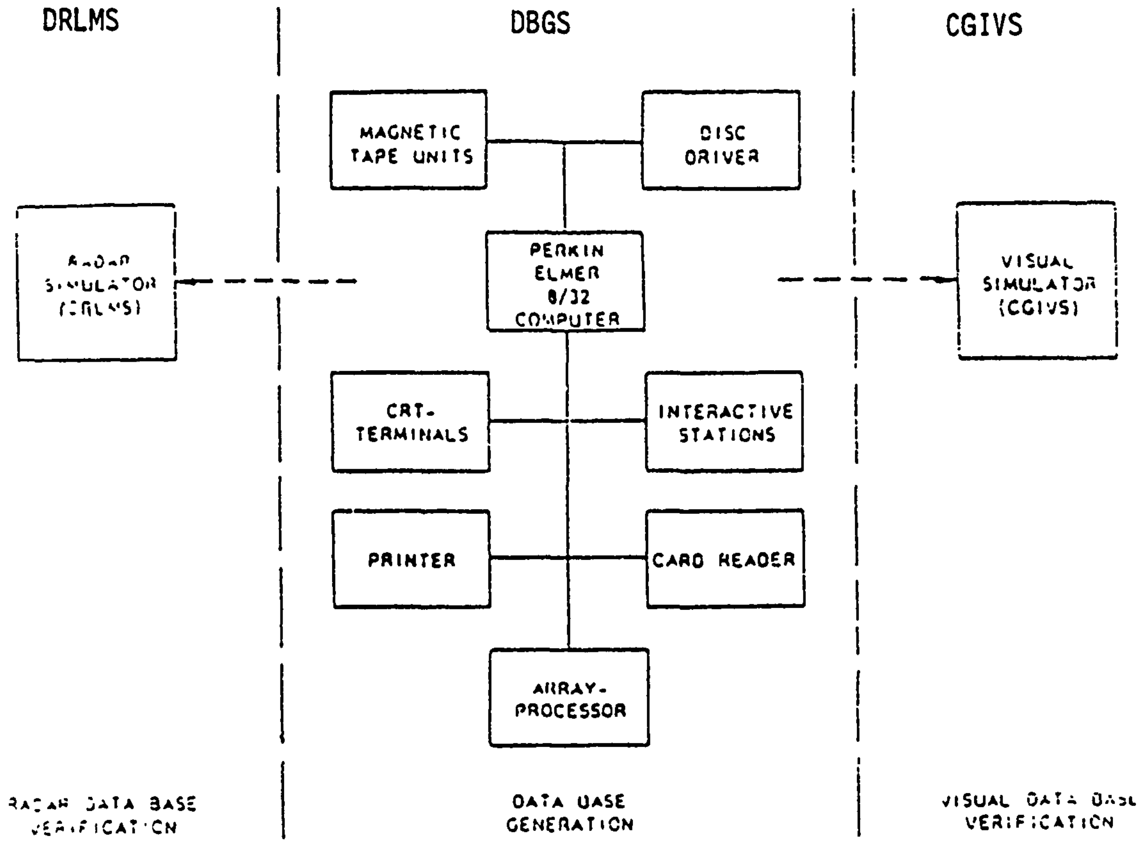

Figure 3: Hardware Configuration

Hardware Configuration (see figure 3.)

The Data Base Generation System is a stand-alone computer complex with computer peripherals. It can be operated independently from the simulator and consists of three main groups: Computer System, Display System, and Interaction System. Only commercial hardware is used. The system has the following configuration:

a. One Perkin Elmer 8/32 Minicomputer with 1 MB Functional Storage, Writeable Control Store and Floating Point Unit.

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b. One type AP 120b Array Processor developed by Floating Point for parallel performance of time consuming procedures.

c. Two Perkin Elmer Type 550 CRT terminals which enable simultaneous communication with the computer.

d. One card reader (1000 CPU) and one line printer (300 LPM), developed by Perkin Elmer as additional input/output peripherals.

e. Two 9-track, 1600 bpi mag-tape units for the input of large amounts of data.

f. Three magnetic 300 MB disc drives for the storage of completed data bases.

g. Two interactive stations, each consisting of one Tektronix 4014-1 graphics terminal, and one Tektronix 4954 digitizing tablet for parallel graphical data processing. The picture content of one graphics terminal can be documented using one Tektronix 4631 hard-copy unit.

This hardware configuration enables the transformation of DMA data, interactive data base generation and modification, as well as batch processing for the generation and modification of data bases for CGIVS and for DRLMS.

VISUAL SIMULATION SYSTEM/DATA BASE GENERATION

Data Base Sources

The source material for the Data Base Generation System is digital landmass data. To satisfy the tremendous requirement for such data, the military geographical agencies or the NATO countries have defined one standardized format in which the information on geographical charts is digitally stored.

There are two types of DLMS data: terrain data and culture data. This information for the same area is stored on two different magnetic tapes. The terrain data represent altitude data at the cross-points of a grid system. The grid systems are divided into five different zones according to latitude, so that each square has an edge length of 100 meters for the coarser level of detail (level 1), and 30 meters for the finer level of detail (level 2).

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The culture data describes the natural terrain structure and the artificial cultural features of the terrain. These are points, lines, and faces defined, which are numbered by an analysis code. Information concerning the geographical position and dimension, as well as the material category and the identification code, is attached. Thirteen different material categories represent, for example, water, earth, rock, metal, etc. By the use of the identification code, characteristics can be differentiated in very great detail. For example, different shapes of roofs or bridges can be discerned.

Terrain Transformation

An algorithm is used in the Data Base Generation System which enables the triangulation of DLMS terrain data in a way that the advantage of variable information density can be used. The logic of this algorithm is based primarily on "trial" and "error". The trials are performed for a certain number of DRLMS grid-points, for which the standard deviation and maximum error in comparison with the triangulated terrain is computed and is compared with defined maximum values.

Culture Transformation

The DLMS face characteristics are projected on the triangulated terrain so that a face subdivision is performed. The attributes of these faces can be gained from the information on the material category and the identification code. For point features, only the positions will be transmitted during transformation. During the interaction it must be decided whether a line feature describes, for example, a river such that a long stretched face has to be projected into the terrain, or only a bridge has to be shown, which is called up from the model library.

Further data on texturing and curved shading are allocated interactively.

Interaction

In order to correct the deficiencies in the digital source material and those which have been introduced during the transformation program, it is necessary to perform interaction during the different phases of the data base generation. One starts with non-digital source material, as for example geodetic charts, air-photographs, etc. The information of those data mediums are brought into the data bases by use of the interactive station.

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The hardware of the interactive station consists of a graphics terminal, a digitizing tablet, and a hard-copy unit. The source material is positioned on the digitizing tablet and is scanned by means of a digitizer. The digitizing process is traced on the graphics display. A cursor defines the position of the digitizer unit. With a menue attached to the digitizing tablet, or by means of the alphanumeric keyboard of the graphics terminal, additional information can be put in. The interactive station is supported by a complex software package which allows one to select certain data as well as to change or input new data. This software package limits the menue effort to a minimum and is user friendly.

Correction of DLMS-Data

Before the transformation process starts, it has to be ensured that the available DLMS data are in accordance with the convention of the DLMS specifications. Experience has shown that the number of errors which have to be corrected interactively varies according to the care with which the data was collected. In this phase, single characteristics can be changed or completely new characteristics can be added to the DLMS format.

Correction of the Online Data Bases

All necessary information which cannot be gained from the DLMS data bases must be added interactively after the transformation has been performed. These are primarily the lines of communication which, to a certain extent, are not existent in the DLMS data bases. Further data on new faces or models has to be added where the transformation program shows only non-identified lines or point features. Additionally, more models can be superimposed. Finally at this stage, interaction is necessary in order to allocate specific attributes such as color, texturing, or curved surface shading as well as the creation of universal features.

Generation of three-dimensional Objects and Models

For the model library a complex store of objects and models is created. This is necessary in order to describe the different culture features in the terrain. The basic forms of simple objects are read-in on the digitizing tablets from construction drawings. These objects can be varied by simple geometrical operations like scaling, mirror inversion, rotation, etc. Complex models can be built up interactively from different objects. The German Airforce and Navy require a complex model library. The models include a drilling platform, mine shaft superstruc-

ture, chemical plant, coke plant, refinery, transformer yard, processing industries with different shapes of roofs, scrap yard, rotating cranes, railway stations, different types of bridges, open-ended stadiums, family houses, castles, residences, hospitals, different types of church towers, airport control tower, runways, aircraft parking areas, taxi ways, drydocks, navigation light ship, light houses, etc.

Data Base Verification

The completed data bases are demonstrated on the graphics display of the Data Base Generation System. The geometrical construction of the data bases can be evaluated. However, all attributes are only numerically indicated (code tables). In order to get a complete impression of the data bases with respect to texturing, curved surface shading, color and the three-dimensional relationships, it is necessary to demonstrate them on an actual CGIVS. By performing this verification, the data base will also be evaluated with respect to the dynamic appearance. The verification might result in the need for corrections, which can be accomplished in one of the above mentioned steps.

Verification of data bases on the real CGIVS is now used only temporarily. In order to prevent use of the simulators at the squadrons for data base generation, it is planned to extend the Data Base Generation System by adding a non-real-time Computer Generated Image System.

German Data Base Visual Requirements

For the time being the German Airforce and Navy require the following complete data bases:

a) Navigational area of upper Bavaria, including an airforce base an a NATO-standard bombing range.

b) Sea area with a coastline

c) Seaport

d) Complex model library - The generation of simple objects and models has been mentioned before. More complex models to be designed are:

- Fighter aircraft
- Transport aircraft

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- Tanker aircraft
- Typical kinds of ships
- Ground vehicle (heavy)
- Ground vehicle (medium heavy)

By the mid-1980's the German Airforce and Navy will create their own data bases in a common data base generation center using the equipment here described.

RADAR SIMULATION SYSTEM DATA BASE GENERATION

The Data Base Generation System also makes it possible to generate data bases for the Digital Radar Landmass Simulation (DRLMS) System. In order to gain a DRLMS data base, a transformation of United States Defense Mapping Agency (DMA) source data is performed. The system allows interactive modification of the DMA data bases or the generation of new data bases from topographic charts. The same hardware is used for generation of both the radar and visual data bases. Verification of completed data bases is performed on an actual DRLMS, at least for the time being.

Automatic Transformation

The on-line DRLMS data bases are produced from the source material by means of a translator program where the grid format is automatically transformed into a compressed vector format. The translator program consists of two parts: the terrain transformation and the culture transformation. Both processes are performed separately and the information is later combined to achieve the on-line DRLMS data bases. The transformation program uses a variable compression technique with the following characteristics:

The terrain is approximated by plane faces which are constructed with lines (vectors). One vector indicates a change in the elevation. The number of vectors which are necessary to model a given terrain is dependent on the roughness of the terrain and the required accuracy of the image.

Isolated objects such as towers and power pylons are defined as point targets. Point targets can be identified by their radius, their height above ground, and by their directional or nondirectional reflectivity characteristics.

Characteristics with length dimension (e.g. bridges, streets, etc.) are defined by line segments. Height above ground and reflectivity data can be added.

Large area features like lakes, irregularly shaped buildings, etc., can be defined by multiple line features. Height and reflectivity data are added. Each data point that is stored includes information concerning position and height in respect to the foregoing value. Therefore, all of these values can be defined as vectors. In comparison to code techniques with constant grid distance, the variable compression technique results in a substantial saving of storage capacity. This allows a much better and more realistic image in systems of comparable storage capacity.

Interactive Data Base Modification

After having performed the first step of transformation, the data base can be improved interactively. In addition, there is the possibility of modifying existing data bases by subtracting or adding parts or changing the reflectivity. Directional characteristics can be added and features can be changed in respect to length, width and height.

Interactive Data Base Generation

An additional program of the DBGS allows data base generation without using Defense Mapping Agency Data. Interactively generated terrain data are formated in a way that they are compatible with data received from the automatic transformation program. In addition, interactive generation and formatting of culture feature data can be performed.

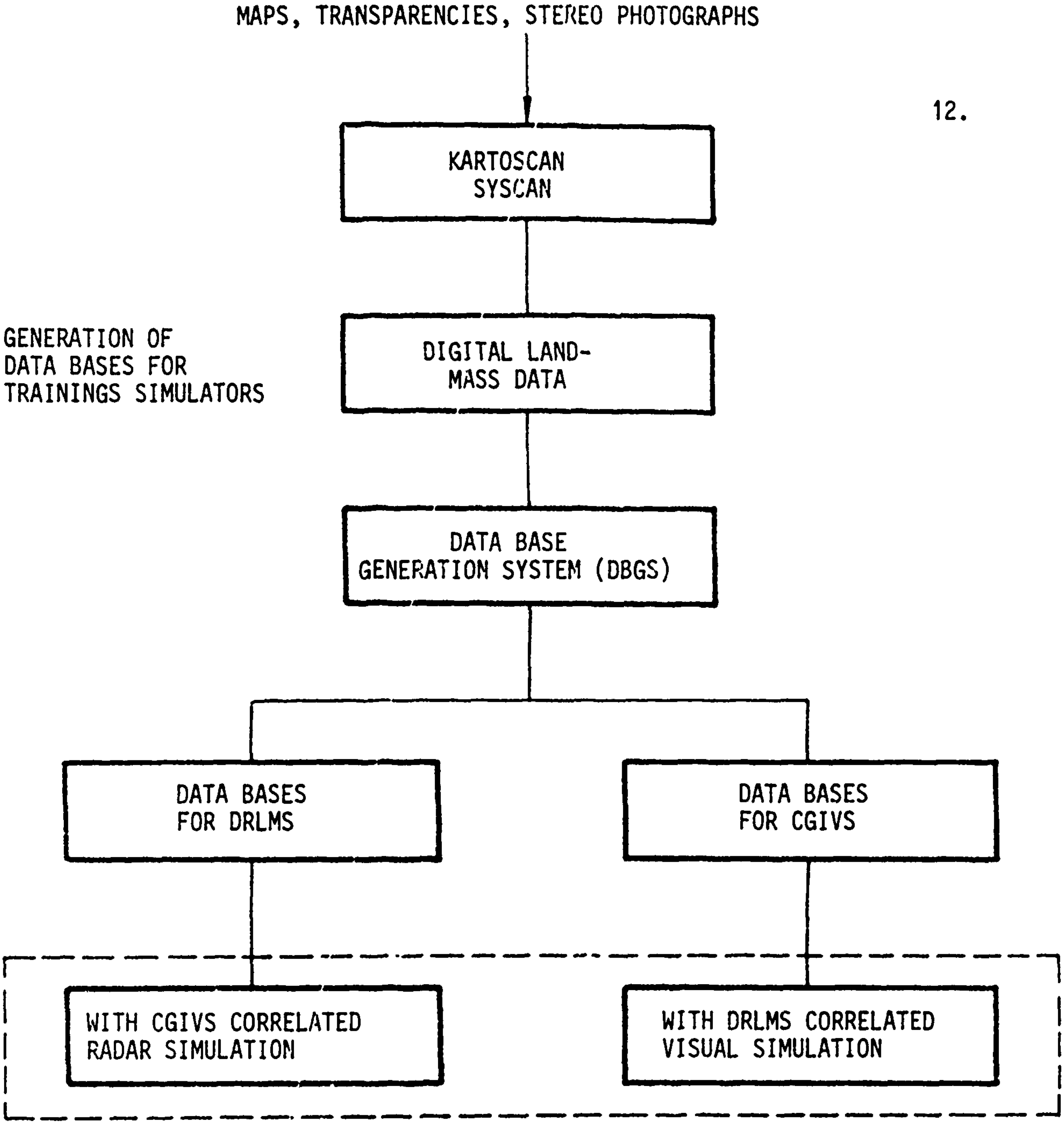
Verification and Requirements for Radar Data Bases

The data bases gained from the DBGS process can be verified by means of the actual DRLMS. The same applies for modified radar data bases. Using the DRLMS, the realistic dynamic appearance is evaluated. However, in order to use the actual DRLMS only for training purposes, the Data Base Generation System will be extended by computer peripherals so that the verification process can be performed with the Data Base Generation System.

At present, a real-time DLMS data base is required for upper Bavaria.

Visual and Radar Data Base Correlation

Visual data bases as well as radar data bases are developed by industry with the assistance of the user. Figure 4 shows the data base generation for CGIVS and DRLMS systems. By using the identical source material, correlation of the displays for both simulation systems is possible.



	PROTOTYPE CGIVS	A PRODUCTION CGIVS
Edges/Scene	2000	8000
Pointlights/Scene	1000	4000
Faces/Scene	500	4000
Real Time Data Base Capacity	10000	40000 plus Dynamic Loading
TV-Lines	525	875
Raster Elements/TV-Line	512	1000
Texturing	NO	YES
Curved Surface Shading	NO	YES

Figure No. 4

Lt. Col. Manfred HAAS is assigned to Headquarter, German Air Force, Director Air Armament stationed at Cologne where he is the officer responsible for simulator requirements. He has worked on the following simulator programs: F-104, F-4F, RF4E, Alpha Jet and Tornado. He played an active role in evaluation of the digital visual system and radar system for the Tornado training simulator. Lt. Col. Manfred Haas was formerly an active F-104 pilot.

Mr. Diether ELFLEIN is a senior engineer in the German Government service. He participated in a number of international programs. He is now member of the Program Office MRCA (Tornado Aircraft) responsible, among others, for the operational flight training simulator. Mr. Elflein holds a Masters degree in engineering from the Technical University in Munich.

Peter M. Güldenpfennig is Program Manager Trainings Systems at the Dynamics Division of Messerschmitt-Bölkow-Blohm GmbH. Mr. Güldenpfennig holds an M.S. degree of engineering from the Technical University of Berlin.

SESSION IV

Display Considerations
Part I

DAVID P. GLENN, Session Chairman
Naval Training Equipment Center
Orlando, Florida

David P. Glenn grew up in Alabama and received a BS degree in Physics from Southwestern at Memphis in 1960. He obtained a scholarship from the University of Florida and completed the requirements for an MS in Physics in 1962. While at the University of Florida, he worked as a consultant to the Air Force Eastern Test Range for the reduction and analysis of rocket plume radiation data.

Upon graduation from the University of Florida, Mr. Glenn was employed by Pan American World Airways at Patrick AFB, FL where he worked as a design engineer for the development of photo-optical and electro-optical instrumentation in support of early missile launch and re-entry programs. He later served as Air Force Program Manager for numerous projects, both land-based and airborne, involving research/development and operational equipment. Perhaps the most widely acclaimed of his projects was the Apollo/Range Instrumentation Aircraft -- a fleet of eight EC135N aircraft which were extensively modified to provide world-wide telemetry and communications support for manned and unmanned missile and space tests. These aircraft are still very active today in the support of missile and space programs. In addition to his work at Patrick AFB FL, Mr. Glenn also obtained an MBA degree in Management from Florida State University.

In 1975 Mr. Glenn and his family moved to Washington DC to attend, in residency, the Industrial College of the Armed Forces. Upon graduation he went to the 4950th Test Wing at Wright-Patterson AFB OH to complete a commitment to manage the successful transition of ARIA operation from Patrick AFB FL to Wright-Patterson AFB OH. Mr. Glenn then became Assistant Director of the Simulator System Program Office at Aeronautical Systems Division where he was involved in formulating and implementing strategies and procedures to improve the acquisition process for Air Force simulators.

In January 1982 Mr. Glenn returned full time to the world of research and development as Director of Research at the Naval Training Equipment (NTEC) in Orlando, FL. In this role, he formulates research programs and policies, and manages a full spectrum of investigations in search of ways to improve Navy training and training devices.

SODERN VISUALIZATION SYSTEM (SVS) FOR FLIGHT SIMULATION

François-Xavier DOITTAU is graduate from the Ecole Polytechnique (Paris, 1965) and from the Ecole Supérieure d'Electricité (Paris, 1967).
He joined SODERN in 1967 as head of the electronics engineering section.
He has been in charge of high and low level pulse electronics, and very low level d.c. amplifiers.
Since 1970 he has been in charge of the design and development work of infrared Earth sensors, cameras using CCDs, star trackers for satellites and missiles and of visualization systems.
He is presently Deputy Director.

Jean R. HURIET is graduate of the Institut d'Optique (Paris) and then he became doctor-engineer at the Paris University. His 25 years professional experience has been in research laboratory, scientific satellite management, before he came to SODERN in 1970 for space projects management.
He is in charge of the SODERN Visualization System program since 1978.

Maurice TISSOT received his PhD in theoretical physics in 1963. He is working since 1974 on SODERN advanced projects at system design level. He is currently responsible for exploring new Titus light valve operation modes for display applications.

SODERN VISUALIZATION SYSTEM (SVS) FOR FLIGHT SIMULATION

Abstract

The Titus light valve is actually a two-dimension analogical memory which is electronicaly controled. It is well adapted to flight simulation requirements because it supplies high resolution, high brightness, flicker-free images.

The SVS (SODERN Visualization System) uses three Titus light valves to project full color images at 30 Hz rate. Already developed models supply good quality images ; further improvements are foreseen in near future, especially for geometrical resolution.

1 - FLIGHT SIMULATION REQUIREMENTS

The two main quality parameters of an image of the real world are : geometrical resolution, and luminance level.

High resolution means also sufficient contrast to observe it.

Concerning geometrical resolution, the objective of the simulation is to reach the eye angular resolution : one arc minute.

For combat aircraft, a very large field of view is needed, which may cover more than 50 % of the sphere. In such a case, the total pixel number reaches 10^8. Moreover, such an image must be supplied at a 30 Hz rate. Displaying 3.10^9 pixels per second is far away from what is physically achievable, even if about 10 projectors are used to cover the whole field.

To cope with this big difficulty, a possible solution is to restrict the high geometrical resolution to the area where such a resolution is really needed Two approaches are possible :

- the high resolution area is limited to a small field covering mainly the pilot's foveal field of view, this high resolution field being servo-driven to the pilot's eye line of sight,

- the high resolution area is limited to the image zones where details are necessary, aircrafts, targets,for instance.

In these two cases, the high resolution area could be inserted by electronic or by mechanical means. The mechanical solution consists in displaying the high resolution area by means of very narrow field of view projectors optical axis of which is servo oriented, in addition to or inserted in the background image. The electronic solution consists in inserting the high resolution area within the field of each projector, at the light valve level, the area position being controled by the scanning electronics.

Image luminance is the second main parameter for a good quality image : it must be higher than 10 f.L. to guarantee a sufficient color and detail visual perception. As a consequence, the luminous flux of one projector must be higher than 2500 lm for 90° field of view. This is the case when using a dome, because the screen albedo must be lowered in order to avoid sphere integration effect which heavily lessens the image contrast ratio. This is again the case when using a dodecaedron field sharing, with pancake windows, because of low optical transmission of these devices.

2 - THE TITUS LIGHT VALVE

The Titus light valve active element is a $KD_2\ PO_4$ (DKDP) crystal slice ; this material exhibits a high electrically induced birefringence effect when cooled down near its Curie temperature (220 Kelvin = - 53° Celcius). The crystal slice is illuminated by a constant, plane polarized light flux ; after crossing the crystal, the light polarization becomes elliptic, this polarization modulation being dependent on the electrical field applied between the crystal faces. This polarization modulation is transformed into luminous flux modulation by a polarizer/analyser whose axis is perpendicular to the incoming polarization direction.

In order to obtain a two-dimension modulator, the applied electric field must vary throughout the crystal area, giving an electrical image.

This electrical image is obtained by laying down electrical charges on the crystal backface, using a scanned electron beam.

The electronic and optical inputs are kept apart by a dielectric mirror deposited under vacuum on the crystal backface.

The writing electron beam has a constant current, the modulation signal being applied between a transparent electrode on the crystal front face, and a grid facing the crystal back face.

The light valve target outline is summarized by next figure.

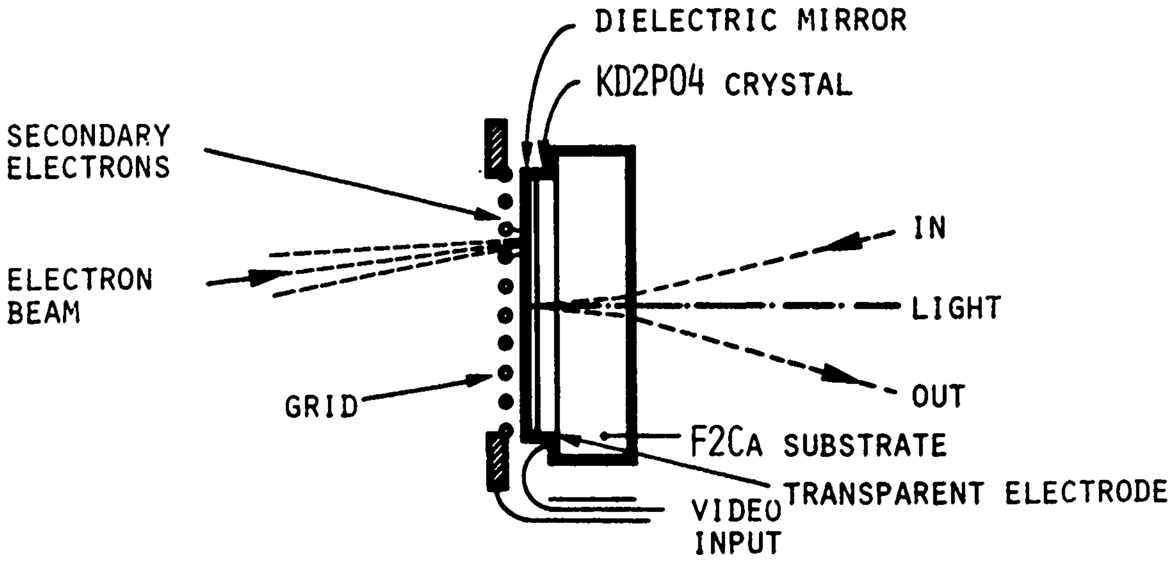


Figure 1 - Titus light valve target schematics

When electrons fall on the dielectric mirror, it results secondary electrons which are either falling down or attracted by the grid. The electrical charge which remains on the dielectric mirror depends on the electric field present between the grid and the target, and then depends only on the video signal. This double elecuron flow allows to increase or decrease the local electrical charge, and then to get a local charge density value whatever was the previous one.

Then, one image is automatically substituted by another one by local increase or decrease of charge density, pixel per pixel. The electrical conductivity of dielectric mirror having a very low value, the local charge density and then the local image luminance does not vary between two successive scans.

3 - CORRESPONDANCE BETWEEN SIMULATION REQUIREMENTS AND TITUS LIGHT VALVE CHARACTERISTICS

As explained above, the Titus light valve is actually a two-dimension memory. It is a static analogical memory, that is to say permanent if no writing action is made. It is made of an homogeneous crystal which does not show any physical structure at the pixel level.

The electrical image is written into this memory by the usual serial mode, one pixel at a time.
An independent and constant luminous flux light source is used to read the electrical image. Reading is made in a parallel mode, that is to say permanently for all pixels.

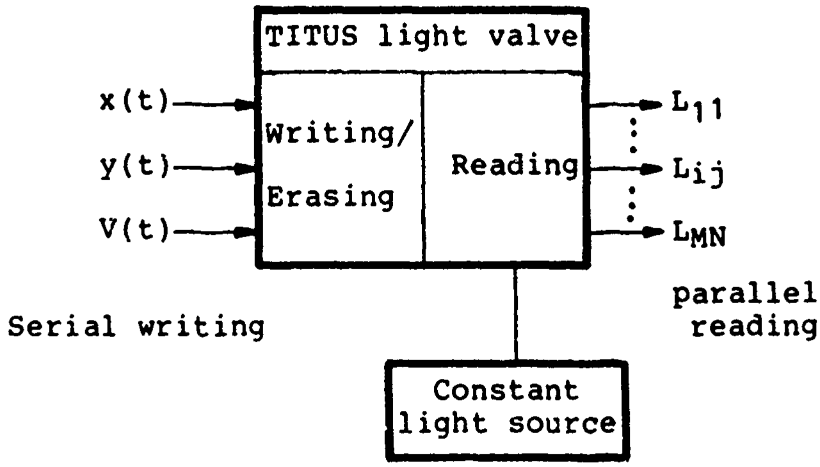


Figure 2 - Titus light valve reading and writing diagram

The serial writing mode exhibit special features which are very important to fullfil the image quality requirements ; these features are :

- Writing of any pixel of a new image without erasing the existing electrical charge corresponding to the previous image ; the former electrical charge is only increased or decreased to reach the new value.

- Image characteristics are, within large limits, independent on writing speed.

- The pixels can be addressed in full random access mode.

All these features allow to get good quality images. Main relations between light valve characteristics and image features are summed up in next figure.

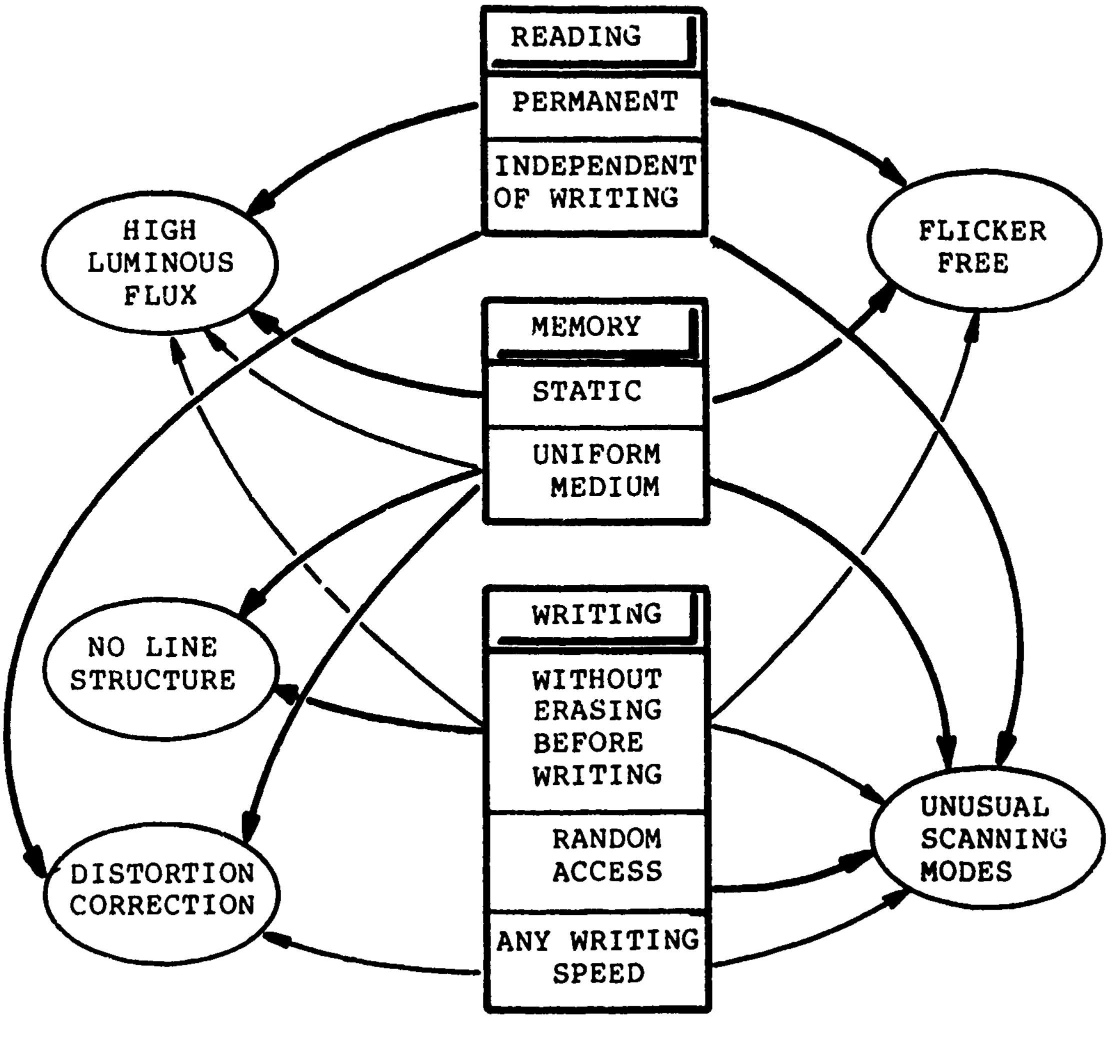


Figure 3 - Connections between Titus light valve features and SVS characteristics

The absence of flicker, which is mainly due to static memory and permanent reading, is achieved whatever the image frequency value is. This is of interest for large field simulators, because the pilot sees the most part of the image through peripheral vision for which the critical flicker frequency is lower than for foveal vision.

The image frequency could be lowered in order to reduce the overall data rate, as far as image motion allows it.

Regarding the luminous flux, independence between light source and spatial light modulation, and permanent reading of memory allows to reach the high flux level which is required.

Geometrical distortion correction can be made at light valve level because the electrical image memory is physically uniform. Such corrections are usefull, especially for projection geometries which are used for simulation purpose : spherical screen, off-axis projection,... In addition, the computer load is lowered when such computations are made within the projectors.

Even if the image is written down in a raster scan mode, line structure does not appear, if the line density is high enough, mainly because the erasing/writing process is a single operation on the uniform crystal target. This allows to vary the line density through out the field of one projector, without any visual result except corresponding geometrical resolution variation.

This possibility opens the way for unusual scanning modes which are interesting to locally increase geometrical resolution. For instance, it is possible to insert a high resolution area anywhere in the field of one projector by a local increase of the scanning line density and by a lower scanning speed in that area.

4 - SVS DESCRIPTION

The SODERN Visualization System (SVS) is a projection system specifically designed to be used in flight simulators.

Full color is obtained by using three light valves, one for each of the three primary colors, red, green and blue.

Next figure represents the optical schematics of the visualization system with Xenon arc as luminous source.

Light produced by the Xenon arc is polarized (reflected component) by the polarizer which holds the optics aperture diaphragm. The plane polarized light is collimated by the objective lens, at the back focus of which, the light valve target is placed. Light is reflected by the target but becomes elliptically polarized, local ellipticity being an increasing function of the voltage locally applied on the target.

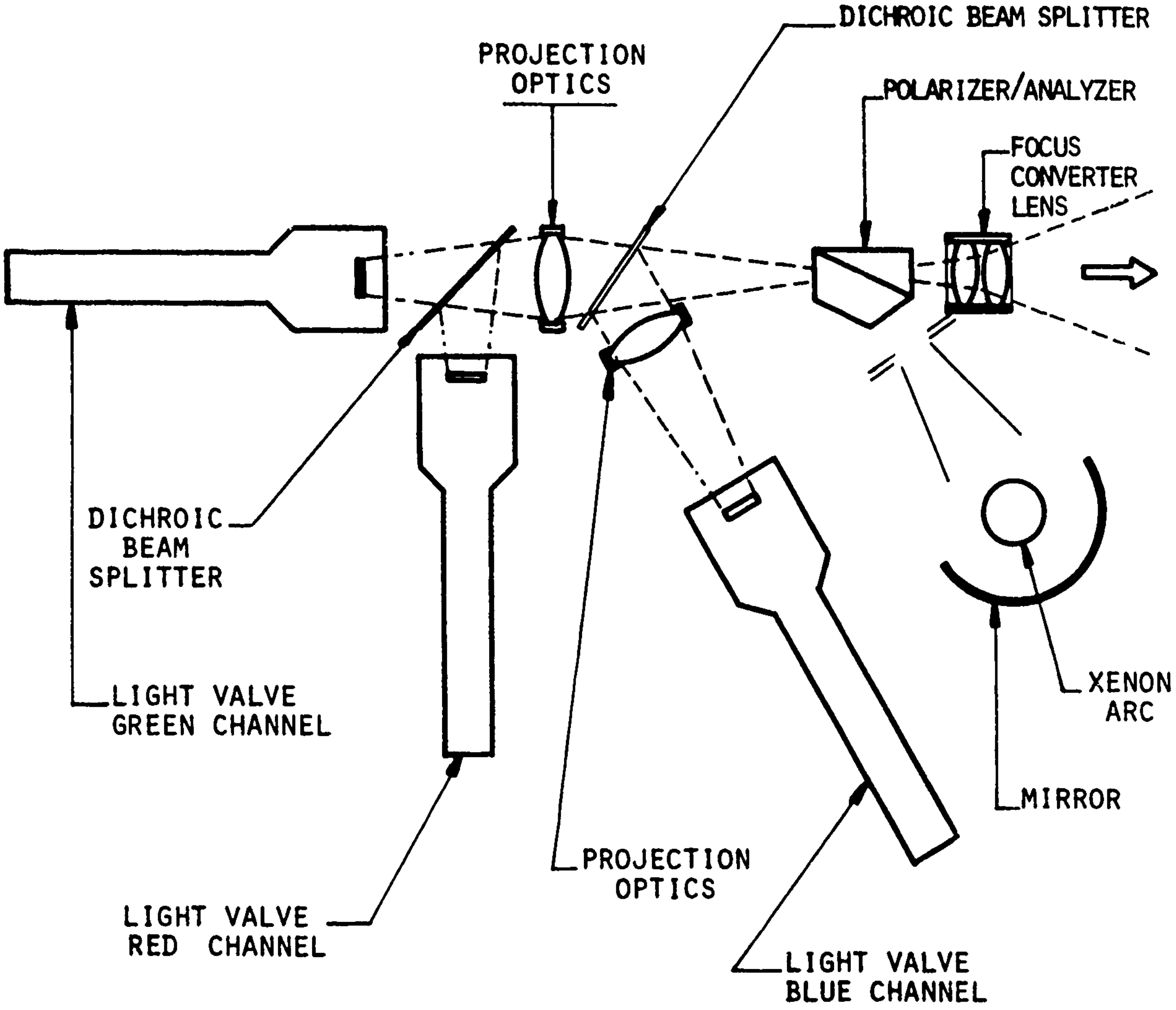


Figure 4 - Optical schematics

The optics placed before the polarizer (illumination optics) and after the analyzer (focus converter) is common for the three components. Blue and red reflecting beam splitters are introduced between the polarizer and the three light valves ; the practical arrangement requires an extra objective lens (projection optics).

In the illumination beam, cold mirrors and ultra-violet filters are used in order to minimize the power dissipation due to absorption in the critical optical components ; field and aperture stops are introduced in order to reduce straylight (image contrast improvement).

In the output beam, the focus converter lens is an afocal device which is used to adapt the field angle to customer's needs ; it also allows to improve the quality of image delivered by the objective lenses. Non infinity focussing adjustment is produced by light valve axial displacement.

5 - PERFORMANCE IMPROVEMENTS

SVS and light valve developments are managed the same way.The main objective is to increase the overall geometrical resolution. The resolution is mainly limited by the light valve itself and by the video bandwidth of the system.

The video bandwidth has been increased from the initial 5 MHz needed for the TV standards with 525 lines/30 frames per second, or 625 lines/25 frames per second ; it presently reaches 18 MHz at full amplitude which corresponds about 1000 pixels/line with 1023 lines/30 frames per second.

The light valve development started with the TV-1 type ; this light valve had a MTF (Modulation Transfert Function) limited to 10 % for 500 pixels per line. The next light valve generation, called TV-2, was designed in order to improve MTF. This was achieved along two steps corresponding to 20 % and 30 - 35 % MTF for 500 pixels per line. Next step is to reach 50 %.

All the above mentionned light valves have a 4/3 field aspect ratio. For simulation purpose, a new light valve, SVS type, was developed with a 1/1 aspect ratio.

Next table summarizes the successive steps of the SVS development, and the main performances.

With the exception of the SVS-15, which uses only one light valve and then supplies black and white images, all other equipments supply full color images with three light valves.

SVS TYPE	ASPECT RATIO	COLOR	SCANNING	LUMINOUS FLUX	RESOLUT. LIMIT PX/LINE
PGE 01 A	4/3	FULL	625 1/ 25 Hz	1500 lm	600
SVS-12	4/3	FULL	1023 1/ 30 Hz	1900 lm	700
SVS-23	4/3	FULL	1251 1/12.5 Hz	1300 lm	800
SVS-15	4/3	BLACK/ WHITE	625 1/ 25 Hz	1500 lm	750
SVS-14	1/1	FULL	1023 1/ 30 Hz	2300 lm	750

Table 1 - SVS main characteristics

6 - OUTLOOK ON THE FUTURE

It has been demonstrated that the SVS is well adapted to simulation requirements. Its performances have been continuously improved and it will be kept on upgrading.

Concerning geometrical resolution, present limitations mainly come from technological difficulties : crystal quality, transparent electrode characteristics (optical transparency, electrical conductivity), grid manufacturing, electron optics and video bandwidth. These problems are progressively solved by continuous improvements. Beyond technological problems, there are physical limitations. As far as the geometrical resolution is concerned, physical limitation is far away from present performance.

In fact, some light-valves named photo-Titus have been manufactured ; the main difference between them and the Titus light valve is relative to the writing mode : the electrical image is built by charges generated into a photo resistant layer deposited onto the crystal back face.

The speed of this writing mode is much lesser than the speed obtained with an electron beam ; it does not permit to reach the 30 Hz image frequency. With this photo-Titus light valve, a resolution corresponding to more than 5000 pixels per line at 5 % modulation was measured, giving an idea of the resolution capability of electrical image reading mechanism.

The overall Titus light valve MTF is mainly limited by electrical image writing with an electron beam . Physical limitations of this writing method are not for the moment completely known because of the rather complex involved mechanisms. It is foreseen that the present pixel number will increase in the near future up to 1500 pixels per line. New steps will be carried out as soon as the writing mechanism knowledge is improved.

Another main point is the luminous flux. Present flux level (2500 lm) may be considered as sufficient ; but it can be increased again by a higher optical efficiency in order to provide the pilot better visual comfort.

Another area of improvement will be open by the implementation of electronic circuits allowing to address pixels with a scanning sequence different from the present raster scan. This possibility will be usefull for writing down small areas of the image with higher geometrical resolution. This is the case for the so called "HRA" high resolution area which can be obtained by a local increase of the scan line density and a lower scanning speed. This is also the case for light points which can be written down with the electronic spot at rest ; such method gives a better positionning, a lower diameter and a higher luminance for the light points.

All above improvements will have benefits on the image quality and on the overall simulator system trade-off between performance and cost.

The movie which is presented demonstrates at evidence the characteristics of high luminous output, flicker-free image and good resolution obtained with the SVS.

AN OVERVIEW OF THE RESEARCH PROGRAM AT THE VISUAL TECHNOLOGY RESEARCH SIMULATOR

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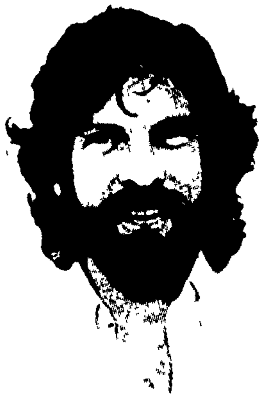

Dennis C. Wightman is a Research Psychologist responsible for the Behavioral Research Program on the Visual Technology Research Simulator at the Naval Training Equipment Center in Orlando, Florida. He has been employed at the Naval Training Equipment Center since 1978. He received a Ph.D. in Psychology from the University of South Florida in 1983. His primary interests are in the area of part-task training, perceptual-motor-skill, and the application of simulators to the training process.

Daniel P. Westra earned his Ph.D. in Human Factors Psychology from the University of South Dakota in 1978. Since being employed at Essex Corporation, he has been at the Naval Training Equipment Center's Visual Technology Research Simulator. He is currently involved with multifactor research programs investigating simulator design features for the carrier landing and air-to-ground weapons delivery tasks. His interests include economical multifactor experimental strategy.

AN OVERVIEW OF THE RESEARCH PROGRAM AT THE VISUAL TECHNOLOGY RESEARCH SIMULATOR

ABSTRACT

The behavioral research program at the Visual Technology Research Simulator is in its sixth year. Although research has emphasized visual issues in simulator training of flight skills, other hardware and instructional technology issues have been explored. This paper outlines significant features of the program's research plan and summarizes the major results.

INTRODUCTION

The Visual Technology Research Simulator (VTRS) has two cockpits. One is a fully instrumented T-2C (fixed wing) Navy jet trainer cockpit with a six-degree-of-freedom motion platform, a 32-element g-seat, and a wide-angle visual system that can project computer-generated images. The maximum field of view subtends 160 degrees (H) by 80 degrees (V). A model board image generation system was available early in the program, but it was removed after the first experiment revealed no difference in performance with model-board or computer-generated images.

The other cockpit has SH-60B (rotary wing) instrumentation and dynamics. It also uses a projection system to display computer-generated images. The maximum field of view is 160 degrees (H) by 70 degrees (V). The system has a g-seat but no motion platform. The interior surfaces of domes, in which the cockpits are mounted, form the projection screens. The radii of the domes and screen distances from the cockpit eye position are 10 feet for the fixed wing simulator and 17 feet for the rotary wing simulator. One primary function of the VTRS is to explore out-of-cockpit visual display issues as they relate to flight training.

The overall research plan is to examine sequentially several tasks that are of interest to the Navy. Fixed-wing carrier landing was the first, and fixed-wing air-to-ground attack and rotary-wing landing on small ships are now being investigated. Within this overall plan, there is a strategy of successively approximating the final definitive experiment for any one flight task. A simulator-to-airplane transfer study is considered to be the final and crucial step, but such a study is expensive and difficult to conduct properly. A nontraining or performance study is the first major step in the investigation of a specified flight task, and this is followed by one or more within-simulator or quasi-transfer studies.

Although the performance studies provide very limited information about training effectiveness, they do serve to

validate experimental manipulations and performance measures. In addition, we have used data from performance studies to exclude some experimental manipulations from later training studies. That procedure is based on the assumption that a variable that does not affect performance is unlikely to produce any differential effect in subsequent transfer to a standard condition. Skilled pilots have been used as subjects in our performance studies, so that these results do have some implications for simulators that are used for skill maintenance and transition training. Conditions shown to help simulator performance may be considered desirable for skill maintenance simulators, although data from this type of study do not indicate whether there will be any subsequent enhancement of flight performance.

The bulk of research at the VTRS has been in the form of quasi-transfer studies. In these studies, a variety of simulator conditions are used to train independent groups of subjects. After a predetermined period of training, subjects are transferred to another simulator condition, considered as the criterion condition, that is as similar to the aircraft as possible. Additionally, a control group is usually included in the experiment. This group is trained and tested on the criterion simulator configuration.

Quasi-transfer studies are used further to examine variables that may affect training. Those that have survived the performance studies, and others that preexperimental work or other research has suggested will have a worthwhile effect, are tested in this phase. Quasi-transfer studies were first proposed as a means of screening variables for subsequent transfer studies. While quasi-transfer studies are costly enough, transfer studies are many times more costly. The resources for transfer studies are limited. That is undesirable but inevitable. Quasi-transfer studies help us select the more important variables to be tested in the transfer study and thereby to use resources available for the transfer studies more effectively.

As our program has developed, it has become clear that quasi-transfer has other benefits. For example, we expect more experimental sensitivity than in a transfer study because there is a wider range of options in establishing reliable and valid performance measures, and it is possible to assert greater control over nonexperimental variables such as environmental conditions. In addition, it is possible to develop experimental procedures and performance measures for use in subsequent transfer studies. While transfer studies appear simple in concept, their execution poses considerable difficulties. In the conduct of quasi-transfer studies, experimenters gain an awareness of how to avoid major mistakes and how to resolve the compromises that are inevitable in any field study.

TABLE 1. EXPERIMENTAL FACTORS AND LEVELS FOR PERFORMANCE EXPERIMENTS BY WESTRA. ET AL. (1982)

MISSION: Carrier Landing Task

PILOT EXPERIENCE: High

FACTOR	LEVEL SETTINGS "low"	"high"
FLOLS	TV/CIG	Optical/Model
Field of view	-27: deg + 9 deg vertical, 24 deg horizontal	-30 deg: + 50 deg vertical, 80 deg horizontal
TV line rate	525	1025
Engine lags	7.5 Hz update	30 Hz update
Ship detail	Night point light	Day solid surface
Visual system lag	217 msec	117 msec
Seascape	Gray homogeneous	Wave pattern
Brightness	Ship: 0.40 fL Sea: 0.04 fL Sky: 0.02 fL	2.90 fL 0.50 fL 0.16 fL
Platform motion	Fixed base	Six degrees of freedom
Ship type	CIG	Camera/Model board
G-seat	Off	30 pneumatic bellows

PLEASE NOTE: This page is to replace page 209 in your copy of the Proceedings of the Image III conference.

One of the most significant potential payoffs from quasi-transfer studies is that they may reduce the need for transfer studies. Certain classes of variables might be found to give similar results in both types of experiments. If we can establish this as a general result, transfer methodology might be needed only to test operational transfer and cost effectiveness. Nevertheless, as it now stands, quasi-transfer studies are thought of primarily as preparation for a transfer study.

We have also used the quasi-transfer methodology to explore the relationships underlying transfer between different methods of displaying visual information. Little is known about how flight skills are learned, so that we do not know what skills rely on out-of-cockpit visual information, nor do we know how quickly students might learn to use a normal representation of that information if they had learned control skills with a radically different representation of that information. A line of quasi-transfer research to clarify issues such as these has examined the acquisition of basic flight skills with flight-naive subjects.

CARRIER LANDING (FIXED WING)

Substantial preparatory work was undertaken for the first experiment. Several problems with the VTRS became apparent, and these were corrected over several months. In particular, the model of the Fresnel Lens Optical Landing System (FLOLS), which is a landing aid that indicates vertical displacement from the glideslope, was incorrect. Correction and subsequent validation of the model grew into a major task.

In addition to validating the simulator system, normal preexperimental work was undertaken. An automatic performance measurement package was programmed. This package records positions and rates of aircraft and control parameters at 30 Hz, and also summarizes data in terms of means, variances, and root-mean-squares. Factor manipulations were tested, and a subject briefing guide (Lintern, 1980) that described procedures for the carrier landing task was developed. Preparation for the first experiment required 18 months of substantial effort by the behavioral research team who worked closely during this time with an engineering and computer science staff that had grown with the VTRS since 1977. In those early days in the VTRS program, the successful testing of our first preexperimental subject had required enormous effort and was hailed as a significant event.

CARRIER LANDING PERFORMANCE EXPERIMENTS. In one of the first experiments at the VTRS, Westra, Simon, Collyer, and Chambers (1982) investigated the effects of ten factors on the performance of experienced pilots in the simulator. The factors and levels are shown in Table 1. This experiment represented

our first attempt to apply the economical multifactor methodology proposed by Simon (1973, 1977).

The only substantial effect on critical measures of task outcome quality came from a comparison of two methods of modelling the FLOLS. Glideslope tracking performance with a computer-generated FLOLS was better than with a projection from an incandescent light-source model. This effect was thought to result from the size difference of the two FLOLS simulations. The computer-generated FLOLS had been modelled at larger than scale to overcome limitations in the resolution of the line-scene projector system.

Two other factors had effects that, although smaller in overall impact, were considered potentially important. The daytime ship detail resulted in better approach lineup performance, and the shorter visual system lags resulted in less roll variability during the approach. The other factors had effects that were generally considered not practically meaningful or negligible. Thus, equipment factors generally showed small to null effects in a practical sense, although some had statistically reliable effects. Because the display and simulator factors were varied over a range of interest that was wide and that represented expensive versus inexpensive simulator options, these results show that the simulator performance of experienced pilots on the carrier landing task is not enhanced substantially by high levels of fidelity.

In another of the five experiments at the VTRS, Kaul, Collyer, and Lintern (1980) tested a simple modification to the FLOLS on the performance of experienced pilots. Variable length vertical light arrays were added to the conventional FLOLS to supplement the normally displayed displacement information with descent-rate information. Addition of the descent-rate information improved glideslope tracking performance. A configuration that guided the pilot back to the glideslope (the command mode), was better than another that only indicated deviations from the reference descent rate (the rate mode).

The FLOLS rate-cuing system has been tested further with a shore-based carrier-landing system at Patuxent River Naval Air Test Center. These tests, and later tests on the Dwight D. Eisenhower, were favorable for the system (dubbed "AVCARS" for Augmented Visual Carrier Aircraft Recovery System), and the Navy is proceeding with plans to add the system to all aircraft carriers.

<u>CARRIER LANDING QUASI-TRANSFER EXPERIMENTS</u>. The information obtained from the performance studies aided the design of a subsequent quasi-transfer experiment that used pilots with no carrier-landing experience (Westra, 1982). In general, if a factor effect was considered practically negligible, the factor was either not studied further or it was combined with others.

Thus, the model board image generation system was not used again, and the g-seat, TV line rate, and engine lag factors were not tested further. Elements of scene brightness and seascape detail were incorporated with ship detail into a new scene-detail factor. The optical FLOLS was also dropped from further study since it had resulted in poorer performance, even though it was the more expensive of the FLOLS display methods. However, FLOLS size, which was believed to be primarily responsible for the effect, was studied in a later quasi-transfer experiment (Sheppard, in preparation).

Field of view, which had been investigated only for straight-in approaches, was tested in this quasi-transfer experiment along with approach type (straight-in or circling). Platform motion was tested in the quasi-transfer paradigm primarily because of its high cost implications. Visual system lag was not included in quasi-transfer testing because of a concern that it would interfere with the effects of other variables. FLOLS rate cuing was also included as a factor in the experiment which is summarized in Table 2. There were transfer advantages for the wide field of view and high scene detail conditions, but not for platform motion or for FLOLS rate cuing. As a result of these findings, it was suggested that only field of view, scene detail, and approach type should be tested in a subsequent simulator-to-airplane transfer study.

Hughes, Lintern, Wightman, Brooks and Singleton (1982) addressed the issue of how to treat errors that are committed during the learning process. Specifically, the study addressed the use of the simulator's freeze feature to interrupt an otherwise continuous performance whenever an error was detected. Simulator "freeze" refers here to total suspension of the simulated task. Instructional feedback was given by an instructor during this period. The freeze feature is common in flight simulators and little guidance has been forthcoming about its role in the instructional process.

Twenty-five experienced Air Force pilots were trained in the VTRS under one of three instructional conditions of freeze/reset (the simulated task was frozen whenever an error was detected, instructional feedback was given, and the simulator was then returned to the appropriate position on the glideslope with the correct angle of attack and airspeed so that the pilot could resume the task); freeze/flyout (as for freeze/reset except that the student continued the task from the point at which it had been frozen); and conventional (students learned the carrier-landing task without the use of the freeze). The error criterion that activated the freeze was also varied. In half of the freeze conditions errors were defined only by the displacement from the glideslope, while in the other cases, the error criterion was defined by displacement from glideslope and deviation from the optimum descent rate. Instructional feedback was given after each approach.

TABLE 2. SUMMARY OF EXPERIMENTAL FACTORS AND LEVELS INVESTIGATED BY WESTRA (1982)

FACTORS	LEVEL SETTINGS "low"	"high"
Field of view	-27 degrees to 9 degrees vertical, plus or minus 24 degrees horizontal	*-30 degrees to 50 degrees vertical, plus or minus 80 degrees horizontal
Ship detail	Night point light	*Day solid surface
Platform motion	Fixed base	*Six degrees of freedom
Approach type	*Circling	Modified straight-in
FLOLS rate cuing	*None (conventional)	"Command" rate cuing
Turbulence[1]	Close to maximum flyable	None
Pilot type	Air Force T-38	Navy P-3C

*Indicates setting for the transfer test configuration.

[1] Turbulence was set at half the "low" level setting for the transfer test.

Pilots who trained under the "freeze" conditions developed control strategies that distinguished them from pilots trained by the conventional measures, but no differences were found between groups on performance measures that indicated rate or extent of learning. In response to a post experimental questionnaire, pilots who trained under "freeze" conditions indicated that the simulator freeze was frustrating and added to the overall difficulty of the task. These pilots further reported being more motivated to avoid the freeze than to perform the task correctly during training. The control strategies data and the questionnaire responses indicated that caution should be exercised when using the flight simulator's freeze feature during the training of a continuous control task such as the approach to landing. However, there was no evidence that the method of establishing the criterion for a freeze had any effect.

Two other quasi-transfer experiments have investigated part-task training with the carrier landing task. Two concerns have encouraged our interest in part-task training. First, if practice of the critical elements of a task can be carried out in a simulator in a manner such that total time to develop skill on the whole task can be reduced, a savings in the costs of training time can be achieved. Second, if certain components of the criterion task can be acquired in less expensive part-task trainers, the costs of using expensive simulators can be reduced.

In one of these experiments (Sheppard, in preparation), the carrier landing task was partitioned by suspending the simulated aircraft at a point 1800 feet from the aircraft carrier and on the glideslope to allow the student to practice some critical elements of the glideslope tracking task. The whole task was to land on the carrier deck from 9000 feet out. In addition to the part- versus whole-task manipulation, Sheppard varied the size of the FLOLS (oversize or near-normal size) and tested the rate cuing displays previously examined by Kaul, et al. (1980) and Westra (1982). Training conditions were fully crossed in a 2X2X3 factorial design. Thirty-six subjects were trained for 30 trials under one of these conditions and were then tested on 30 transfer trials under the whole task with the near-normal sized FLOLS and without descent-rate cuing.

Whole-task training was superior to part-task training. Training with the rate mode of the descent-rate cuing resulted in a short-lived advantage for glideslope tracking performance. There was no transfer advantage or disadvantage from training with an oversized FLOLS. Since there is an engineering advantage to the oversized FLOLS display, its use is recommended in the design of carrier-landing trainers.

The lack of any stable descent-rate cuing effect was surprising in light of the positive performance benefit found

for experienced pilots. However, Westra's (1982) results also showed that inexperienced pilots did not benefit from these displays. It would appear that pilots with little carrier-landing experience cannot effectively use the additional descent-rate information.

In another of these part-task training experiments (Wightman, 1983), a task segmentation strategy (backward chaining) and a task simplification strategy (enhancement of the simulated aircraft's response to throttle adjustments) were tested. In addition, motor skill aptitude was assessed with an ATARI video game, designated in our research as Air Combat Maneuvering (ACM). Performance on this task has been found to correlate with carrier landing performance in the simulator (Lintern and Kennedy, 1982). The test was administered to permit examination of aptitude by treatment interaction.

In the control training condition, subjects "flew" 48 carrier landing approaches, starting each one 6000 feet behind the carrier. Subjects in the backward chaining condition started at the 2000-foot mark for their first block of 16 training trials, from the 4000-foot mark for their second, and from the 6000-foot mark for their third and final block of 16 training trials. Three levels of responsiveness to throttle adjustments (very responsive, moderately responsive, and normal) were established by changing the weight of the simulated aircraft (aircraft response to throttle adjustments during the approach to landing is normally sluggish). For subjects in this training condition, responsiveness was adjusted progressively from high to normal over three 16-trial training blocks. The backward chaining and responsiveness manipulations were combined in a fourth experimental training condition. Following training, all subjects were tested on the 6000-foot approaches and with normal responsiveness to throttle adjustments.

In testing on the whole task, subjects trained under backward chaining were significantly better than those trained on the whole task. Furthermore, the effect of backward chaining was modified by motor-skill aptitude; the higher ability subjects quickly overcame the disadvantage from whole-task training, but the lower ability subjects did not. These results imply that the segmentation manipulation was especially useful for subjects with low motor skill aptitude. No significant effects were found with the responsiveness manipulation.

CARRIER LANDING TRANSFER EXPERIMENT

While quasi-transfer of training experiments do yield a large amount of information about the effectiveness of simulator features on pilot training, few facts are quite as convincing as the data developed from an experiment that test pilots in the aircraft on the task of interest. The VTRS behavioral research

staff has embarked upon a transfer-of-training experiment as a culmination of the carrier landing research program.

Four factors, those being field of view (wide or narrow), scene detail (day or night), task type (circling; backward chaining progressing from an extended straight-in approach to whole circling; or backward chaining progressing from short, straight-in approach to whole circling); and number of simulator training trials (20; 40; or 60) were fully crossed to form a 2X2X3X3 factorial design.

Student pilots from the Training Command travel to Orlando and are trained under one of the possible conditions yielded by the experimental design (e.g., wide field of view, day, whole task for 20 trials). They then return to their flight school for the field carrier landing practice phase of the training. Their glideslope tracking performance is monitored with a laser tracking system (called HYTAL for Hybrid Terminal Assist Landing System) developed by the Naval Weapons Center at China Lake, California. This system yields the primary measures that will be used to examine transfer effects.

Data collection for the first full transfer-of-training experiment at the VTRS should end in July of this year. Since the Navy is currently purchasing a complete set of visual flight simulators for undergraduate pilot training, and is concerned about how the visual system should be configured and how the trainers should be used, this experiment has acquired a degree of urgency.

AIR-TO-GROUND ATTACK (FIXED WING)

Air-to-ground attack was identified as the next task for examination in the VTRS. This effort started with a review of Navy practices and procedures (Vreuls and Sullivan, 1982). Of the many tasks that are taught, a manual (not computer-aided) bomb delivery from a 30-degree dive was selected for investigation. This selection was based on the four general criteria of 1) operational relevance, 2) consistency with current training practices, 3) suitability for examining visual simulation issues, and 4) feasibility within the VTRS configuration. The constraints of the last criterion included T-2 aircraft dynamics, an A-4 weapon control panel, and simulation of an optical bomb sight. Bombs, rockets, and guns were available. The 30-degree manual bombing task was chosen as a basic maneuver that is learned by all attack pilots and that offers a substantial learning challenge.

A briefing guide was prepared for the experiment (Berry and Lintern, 1982). This guide described the procedures to be followed for successful execution of the task. An optimum flight path and optimum aircraft states throughout the task were also defined and programmed into the on-line data recording

software so that deviations from optimum could be measured and summarized. RMS pitch, altitude and lateral errors in the dive; altitude, lateral, pitch and airspeed errors at release; and bomb impact errors were recorded along with other measures of aircraft and pilot activity.

AIR-TO-GROUND ATTACK PERFORMANCE EXPERIMENT. Westra (in preparation) examined the effects on performance of visual system lag (117 msec or 217 msec), background offset (120 degrees left and 40 degrees right or 80 degrees left and right), edge segmentation (up to 16 per modelled edge or none), platform motion (maximum or none), and g-seat (on or off). The first listed level of each factor was considered the high-fidelity level. Scene content was also included as a factor with four scenes ranging in type and content from a skeletal grid pattern to a relatively complex scene with mountain ranges and a river valley. Eight Navy fleet pilots, experienced in air-to-ground bombing, participated in the experiment.

The scene-type factor had substantial effects on a number of measures. Notable among these was the clearly superior bombing scores with a landscape containing many cultural factors (i.e., fields, roads, buildings, small towns). This may have been partly due to the better perceptual stability afforded by the three-dimensional building used as a target. Also note that this scene had the smallest number of active edges of the four scenes. If it were necessary to select one scene, this one certainly represents a "best buy" in terms of cost, fidelity, and effectiveness.

Another conclusion to be drawn from the results is that the five simulator factors (other than scene type) had a minor impact on performance. Pilot differences generally accounted for far more variance in performance than did the five other factors combined. This implies that a point of diminishing returns has been reached with respect to further improvements in simulator fidelity for air-to-ground skill maintenance and transition training. It appears that added realism (beyond the low levels of the five factors) should not be purchased at the expense of lower reliability or higher acquisition and life cycle costs.

AIR-TO-GROUND ATTACK QUASI-TRANSFER EXPERIMENT. This experiment was closely followed by a study in which 32 military pilots were taught to deliver bombs from a 30-degree dive (Lintern, Thomley, Nelson, and Roscoe, in preparation). Sixteen of the pilots had a moderate amount of prior bombing experience (approximately 60 bombing runs) and the remainder had none. The pilots were given 80 training trials in the simulator under specific training conditions. Three factors were manipulated in training; those being level of detail in the visual scene, variety of visual scenes, and augmented feedback in the form of artificial visual guidance. Differential transfer effects were assessed on the

basis of performance on 30 transfer trials in the simulator. The transfer phase used a variety of visual scenes and varying levels of detail, but no augmented feedback. All subjects flew the same set of conditions in the transfer phase.

Scene content had a strong and consistent effect on performance and on differential transfer. The same landscape that had produced good performances in the Westra (in preparation) study was generally better than a schematic grid pattern for both training and transfer performances. The results of this experiment did not clearly isolate specific scene features that contributed to this effect, but some likely candidates were identified and these will be examined in future experiments.

The most intriguing observation on scene detail was that pilots who learned the task with the landscape could later perform well with the grid pattern. However, those trained on the grid pattern never exhibited the high level of performance shown by those trained on the landscape. Thus, some of the features of the landscape seem essential for early learning but appear to be less important after some learning has been accomplished.

The scene-content issue is one of the most crucial for modern training simulators. These data are the first to show that scene content affects learning of flight skills. Further research to identify visual features that do impact learning is essential. In the meantime, simulator training of air-to-ground attack should be conducted with visual scenes that at least have features similar to those of our landscape.

Variety was raised as a training issue specifically because modern simulators can provide enormous variety at little additional cost. Scene variety in training did not generally benefit transfer, and there is a distinct possibility that it can interfere with early learning. However, transient disruptions in performance at transfer suggested that brief experiences with a wider range of scenes towards the end of a constant training regimen could be useful. Thus, we recommend that air-to-ground attack be taught initially in a simulator with only one scene and run-in heading, but that a variety of scenes and run-in headings be introduced just prior to transfer. A similar approach might be used in the aircraft if the option exists. In addition, our data suggest that it may be beneficial to simulate attacks on environments that are modelled to look like actual target areas. This might increase the effectiveness of a pilot's first aircraft pass at that target.

Augmented feedback proved to be a potent instructional variable, but one that showed complex effects. It helped inexperienced pilots with their dive pitch control, and helped both the inexperienced and more experienced pilots with their

dive altitude control. The data further indicated that augmented feedback helped the more experienced pilots with their longitudinal bomb miss distance. Thus, the effects of augmented feedback are pervasive and progressive. It would appear to be useful at least for primary and intermediate instruction.

There were several interactions of pilot experience with the experimental variables. In general, the inexperienced pilots suffered most from limited scene content and gained most from augmented feedback. Nevertheless, the moderately experienced pilots were also affected by these variables. Thus, there is no evidence in these data that pilots with no experience in air-to-ground attack should be treated differently during training to pilots who have some experience in air-to-ground attack.

AIR-TO-GROUND ATTACK TRANSFER EXPERIMENT. A transfer study is now planned. Following our results in the performance and quasi-transfer study, scene content issues will provide the focus for experimental manipulations. The current plans are to bring student pilots to the VTRS for prior training and then to test their bombing performance during their normal weapon training curriculum.

LANDING ON SMALL SHIPS (ROTARY WING)

A first experiment has been conducted in the SH-60B cockpit from one-half mile behind the ship. The task was to land on the deck of an FFG7 frigate. As for the carrier landing and air-to-ground bombing, a briefing guide was prepared to describe the task (Lintern, 1983) and a criterion flight envelope was programmed for performance measurement. The experiment was a performance study in which visual system lag (117 msec or 217 msec), g-seat cuing and vibration (on or off), seastate and turbulence (high or low), scene content (high or low), rotor speed sound cuing (on or off), field of view (maximum or restricted), and pilot experience (high or moderate) were manipulated. The data from this experiment are currently being analyzed.

BASIC FLIGHT TASKS

Two experiments have used quasi-transfer methodology to examine the acquisition of basic flight skills with flight-naive subjects under radically different display conditions. In the first of these (Hennessy, Lintern, and Collyer, 1981), subjects were taught to fly straight and level in one of three training conditions; those being a narrow field of view that included a horizon and checkerboard ground plane; an outside view of the aircraft; and a display that consisted only of the normal flight instruments. A fourth group of control subjects learned

the task with a wide field of view that included a horizon and checkerboard ground plane. All subjects were subsequently tested on the control condition.

There was no evident advantage or disadvantage in the testing phase from any of the training conditions. Thus, it appears that this basic flight skill can be learned effectively with a wide variety of visual display types. The results suggested that the perceptual skills necessary to support this task were learned very quickly, while acquisition of the control skills required more time.

In a follow-up of this work, Sheppard and Lintern (in preparation) taught flight-naive subjects to fly straight and level and to make a climbing turn. The two tasks were selected based on earlier work by Ornstein and Fleishman (1966), as ones that might provide contrasting results. Three training conditions were tested, those being 1) wide field of view with a landscape scene and full use of normal aircraft instruments, 2) wide field of view with the extensively detailed landscape but no use of the aircraft instruments, and 3) aircraft instruments without the use of the outside visual scene. These three training conditions also were used in transfer, so that there were six experimental groups that trained on one of the display conditions and transferred to another. In addition, three control groups were included in the experiment. These groups were tested on the same display that had been used in their training phase. The data of this experiment are currently being analyzed.

SUMMARY

Our research at the VTRS has enabled us to move towards a clearer definition of simulator design features to teach flight skills. Progress towards a comprehensive specification of desirable visual display characteristics for flight training simulators has been slow and painstaking, primarily because so little is known about skill transfer and the conditions that affect it. Nevertheless, substantial progress has been made at the VTRS with a programmatic approach to this problem. This research is well on the way to providing definitive answers to questions about costly simulator options.

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THE USE OF LASERS IN WIDE-ANGLE VISUAL SYSTEMS

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THE USE OF LASERS IN WIDE-ANGLE VISUAL DISPLAYS

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Abstract

Performance requirements and associated problems of wide-angled displays are discussed, and possible solutions based on the use of lasers outlined. Included, is a helmet-mounted projector system currently being built for the Naval Training Equipment Centre.

Introduction

Despite the existence of sophisticated flying aids such as zero visibility landing equipment and forward looking infra-red displays, it is generally accepted that 'out of the window' scenes are at present and will remain in the forseeable future an irreplaceable part of commercial and military flight training.

Within the last few years, displays systems having a large field-of-view, let us say at least 120° horizontally by a minimum of 40° vertically, which were previously regarded as fairly special, have become the 'order of the day' for both civil and military training. Also, resolution values of around 6 arc minutes which were for many years better than was usually achieved, now have become an absolute minimum even for commercial training requirements, and most military systems need to achieve 1-4 arc minutes. Also there is a constant demand for the improved resolution to be accompanied by an increase in scene content which has driven the remarkable development in computer image generators over the past ten years.

It is, however, fairly evident that display techniques, despite some improvements, have not advanced as significantly in the same period. It is probably true to say that other than for light points no current system can fully utilise the potential of the more advanced CIG's. For example, although '1000' line scanning standards have been with us for many years it is rare for the projected image resolution to match the best attainable for that scanning standard.

The inherent practical limitations of CRT's were acknowledged by the display industry in the late sixties and with the emergence of the laser a possible alternative seemed to have been found, and in fact since then a great deal of interest has been expressed in laser display systems and a number of very promising demonstrations made.

However, in general, the simulation industry has preferred CRT or light valve based systems although more recently scanned lasers have been specified as the primary source of illumination for both image generation and display in separate military training applications.

Despite the hesitant beginning, the fundamental characteristic of the laser beam, that is its small spot size and high brightness, still holds much greater potential for producing a more detailed image over a large angle than other known devices.

There is every indication that a substantial step-up in the performance of displays systems which is almost certainly required, may not be achieved without utilisation of the laser.

Performance Targets for 'Out of the Window' Scenes

It is not the aim of this paper to investigate the visual requirements of a particular training task or set of tasks. However, it is perhaps useful to state a maxim which has now gained almost universal acceptance.

'For most tasks requiring interpretation of the visual scene, realism and training benefit increases with increasing field of view and scene content'.

This principle arising from a combination of documented evidence and diverse experience gained from a long period of both aircraft and simulator based training, has led to the generation of far-reaching visual specifications which although often demanded are much less frequently achieved.

It is, of course, recognised that there are considerable differences between commerical and military requirements, with further variations for wide-bodied aircraft as compared with tandem or single seat types.

The following parameters are proposed therefore to serve as an approximate guide in discussing visual systems and weighing concepts.

AIRCRAFT TYPE

	Commercial Wide-Bodied	Military Side by Side Two Seat	Single or Tandem Seat
Instantaneous Field of View			
Vertical	40°-60°	40°-60°	60°-120°
Horizontal	120°-180°	140°-180°	150°-240°
Total Field of View	60°x240°	90°x240°	180°x360°
Scene Content (Elements ie: Light Points Polygons, etc)	>2000	5000>15,000	5000->50,000

Limiting Resolution (arc minutes)	3-6	1-6	0.5-3
Image Update Rate (Frames/see)	30	30	30-60
Special Effects	Vehicles & A/C on ground, weather.	Lights/Weapons Effects, A/C in flight	Vegetation, Weather Moving Targets, Weapons effects smoke etc

It may be useful make a few observations and comments relating to the above.

(1) Scene content and image resolution are precious and rarely more than just adequate. Display devices should have sufficient bandwidth and resolution capability to avoid degradation of the generated image.

(2) Although the widest field of view possible may be desirable it may not be worthwhile to increase this to a degree where scene content is significantly reduced.

(3) The over-riding value to training provided by a visual display is within the dynamic scene although resolution for example is usually measured on a static image. It will probably become necessary to design for higher refresh rates in future and dispense with interlaced fields in raster scanned systems, thus increasing further, data rates and video bandwidths.

(4) The instantaneous field of view could be limited with significant performance benefits, if the total field of view is made large by virtue of coupling the display to the pilots look direction. This may not be appropriate for other than single seat applications.

Problems posed by Wide Angle Display Requirements

Scene Content

The potential advantages of large field of view displays are now fully recognised. For example, peripheral cues, large field of regard, enhanced motion cues and greater realism. Other than perhaps for air combat, the increased field needs to contain at least as much detail, per unit area, as was previously regarded as sufficient for let us say a 60" diagonal display. At present

and within the forseeable future a number of separate CGI channels will be needed to achieve this.

A preferred display system will therefore most likely continue as a multi-channel device but should lend itself to performance development within each channel so that CGI improvements may be accommodated. Also in order to allow flexibility in blending and combining one channel with another, and general versatility in fitting various cockpits and different training needs, a projection system is probably essential.

Although CRT's and light valves do offer acceptable solutions at present there is serious risk that these types of projectors will not have sufficient performance to display the rapidly growing scene detail becoming available, and will in any case present an overwhelming packaging and weight problem when more than four or five channels of CGI are required.

Resolution

Resolution performance, very much as with scene content, is for a given display device directly proportional to the field angle produced. Therefore in principal a large total field of view can be generated, having the required resolution, by choosing the appropriate number of channels.

In practice cost, complexity, and loss of scene content per unit area displayed will limit the number channels to between say two and five for most systems. So we cannot easily avoid the need to maximise individual channel performance.

Further, as mentioned earlier, if a genuine resolution performance of 1000 TV lines is still the best obtainable for CRT, light valve, or liquid crystal devices, and allowing that these 1000 pixels are displayed without degradation over no more than a 50° field, the achieved resolution cannot exceed 3 arc minutes.

Projection CRT development continues and new phosphors have allowed advances in light outputs and reductions in spot size but broadly the last 20 years has not produced significant changes. In general improved resolution for a given tube brightness forces an increase in diameter. The larger the tube the more difficult becomes the design of the projection optics especially for larger field angles and the greater becomes the problem of colour convergence and packaging.

Liquid crystal light valves show promise, particularly if laser addressed, although a response time of 30 m.sec. would seem unacceptably slow for flight simulation.

Brightness

Adequate image brightness is probably not too difficult to achieve, providing a sufficient number of channels are being used for other reasons.

However, if say only two channels are appropriate but displayed over a very large field of view as for air combat for example, then a very low brightness will result unless boosted by using specular or retro-reflective screen material. A large angle between the exit pupil(s) and the pilots eye due mainly to the volume occupied by a conventional gimballed projector will prevent any advantage being taken of these materials.

Distortion

Distortion of the image which always tends to occur in display systems would become very severe in many cases unless correction is applied.

The main sources of distortion are:-

(1) Off axis projection - Due to the exit pupil of the projector not being normal to the display screen or because the image is viewed off axis.

(2) Projection optics - Where the image mapping of the projection optics does not match the screen geometry.

(3) Image generator - Where the CGI mapping does not match the screen geometry.

Distortion correction is for most systems, a difficult procedure and will often only reduce errors to an acceptable level rather than effect a full adjustment. The usual approaches to the problem are:-

(1) To carry out a spherical mapping procedure in the image generator and include corrections for off-axis projection.

(2) To segment the display into sufficiently small fields so that cartesian mapping is acceptable in each channel.

(3) To apply correction terms to the x and y drives in the CRT (if used).

(4) Incorporate off-axis or aspheric optical elements to reduce projection or mapping errors.

(5) Arrange that the eye point is as close as possible to the exit pupil.

(6) In multi-channel devices exit pupils should not be widely spaced and near co-incident if possible.

Virtual or Real Image

It is obvious enough that producing a virtual or 'collimated' image becomes increasingly difficult as the field of view is increased.

There are three basic methods of creating a virtual image display.

(1) A mosaic of In-line virtual image windows each containing a separate display device. This approach, although successful in several instances, tends to be expensive, low in brightness, and prevents the image from having a continuous appearance.

(2) A curved projection screen viewed off-axis through a large-diameter collimating mirror.

This method involves the manufacture of very large optical components but can produce the most realistic result. For extremely large display angles a compact single exit pupil projector would be needed.

(3) A helmet-mounted display device viewed through a beam splitter with collimating optics.

This provides the possibility of creating a wide-angle stereoscopic scene without the need for large screens and mirrors. This is not likely to be developed for anything but highly specialised applications.

The use of virtual images for flight training in aircraft with side by side crew seating is universal but in many other cases its use is a matter of preference rather than necessity. As larger display angles are envisaged a directly viewed screen should be employed wherever possible as a welcome simplification.

Wide Angle Display - Some Solutions

A large FOV display system employing CRT projectors (Ref 1)

This is a currently available RSL system developed originally for commercial use and intended to supercede the conventional monitor- based arrangment.

It employs three purpose designed CRT projectors (Ref 2), which project a continuous 150° x 40° image onto a curved screen. The image is viewed from the flight deck through a large radius collimating mirror (fig 1).

The projectors provide colour and are capable of random or raster scan in order to be compatible with various types of image generators.

Adjustments to image geometry required to compensate for off-axis viewing and mapping errors, and provide for accurate edge-matching are effected by a raster distortion technique. Colour matching and soft edge matching are utilised to produce an uninterrupted image.

Thus, a collimated scene is presented to the whole flight deck, allowing application to all types of wide-bodied aircraft, civil or military.

The practical limit of performance using CRT projectors is probably 3 arc mins resolution with a 6 fL brightness measured at the pilots eye point.

The horizontal FOV can, in principle, be extended to 360°, in which case a multi-channel single exit pupil projector would be particularly appropriate.

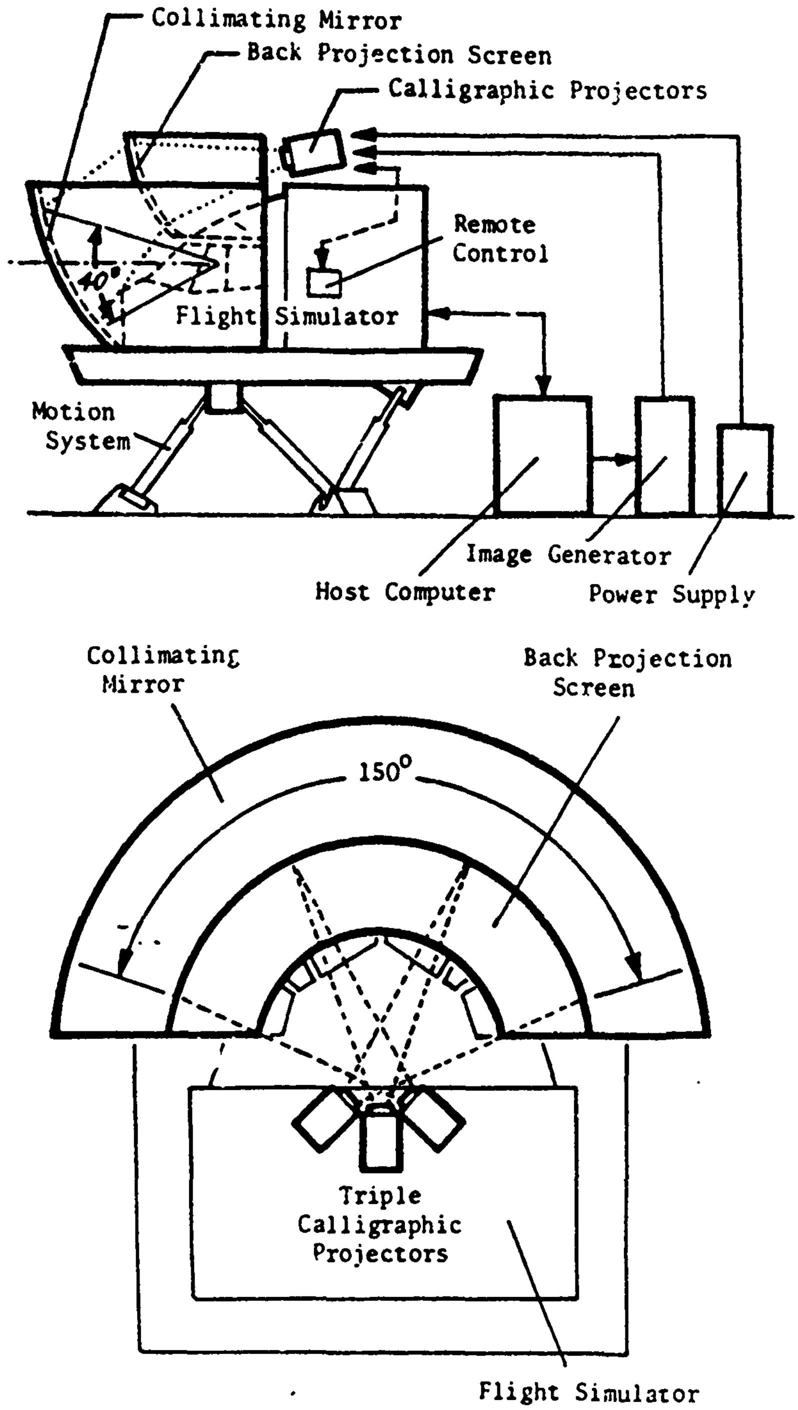

Figure 1

Systems employing scanned laser beams

Given the performance targets stated earlier and the limitations of existing display devices, there are some very stong arguments in favour of using lasers as the primary illumination source.

Unlike the CRT where spot size is traded against light output, the laser beam profile does not change with increasing beam power. In addition very little degradation should occur within the system as the beam will only interact with precision optical surfaces for modulation and scanning.

Also as the beam is generated within about a 1 mm diameter, optical apertures can generally be held to a moderate size so that aberrations are small and often diffraction limited performance achieved. Further, owing to the nature of laser beam modulators the use of large video bandwidths presents no fundamental difficulties.

One of the possible great advantages of a laser projection system is that potentially it can be very compact in the area of the exit pupil. The lasers, modulators, and scanning components for example, can be remote from the cockpit, allowing an RGB recombined scanning beam to be transmitted to the projection head by means of a relay system or fibre optic link. The design of the projection head could then be aimed with purpose at achieving a large FOV from a single exit pupil or from multiple exit pupils, which may be close to the pilots eye point.

A 180° x 60° Scanned Laser Camera and Projector Visual (Ref 3)

This system was designed as a possible answer to the requirement for high scene detail over a wide field defined in the early 1970's for 'nap of the earth' flight simulation.

The system utilised a 100 MHz video bandwidth and 5,280 scan lines per frame. It was demonstrated in breadboard form only but showed convincingly how laser systems lend themselves to novel scanning techniques and the potential advantages of a large continuous FOV (fig 2).

The projector, having a high pixel rate and spherical mapping was designed to accept video from a laser camera and modelboard with similar characteristics, and could not readily be made compatible to CGI. However, despite the limited gaming area available from a 1000:1 terrain model this must still be considered a very cost effective approach to applications which require very rich scene detail over the whole FOV.

Apart from low altitude flight training another possible application for this type of system is in-flight refuelling. The current visual requirements call for many surface markings and other detail to be present, and ideally the full wingspan of the tanker to be within view as seen from the re-fuelling station.

This well resolved, continuous 140° image, needs to be achieved at a cost that would definitely preclude two or three channels of advanced CGI.

This laser camera/projector system used with a good A/C model could produce a very satisfactory visual for a part task trainer.

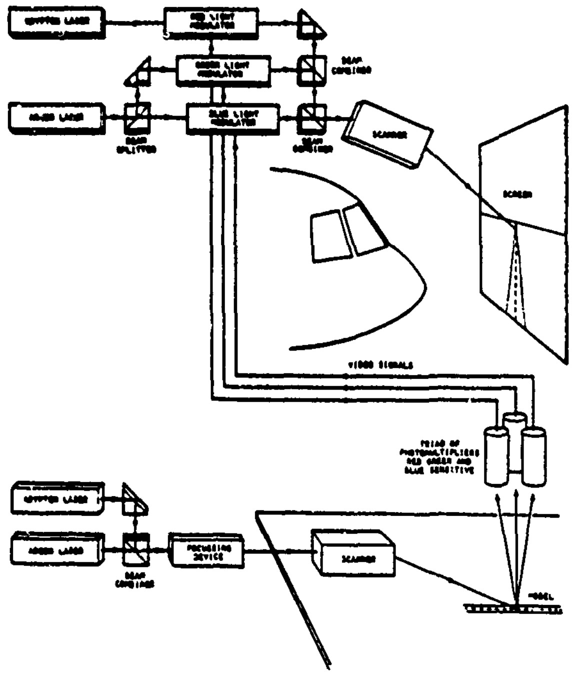

Figure 2

A Multi-Channel Laser Projector

In most cases of course, CGI will be used and a number of channels will be needed to provide sufficient scene detail.

Now, in order that CGI mapped in cartesian co-ordinates is correctly displayed, a suitable CGI 'window' should be chosen so that distortions occurring within that field angle may be corrected.

It is probable that the largest angle for each 'window' or sub-field would be approximately 60° and therefore there is most likely to be 3 or 4 sub-fields to provide the required horizontal Field of View.

Associated with each sub-field would be either a separate projection lens system or if a single projection lens is used, a separate pupil.

It is also useful to note that the number of CGI channels used could be larger than the number of optical channels in the projector output stage.

If CGI mapping in spherical polar co-ordinates is available it may be desirable, for example, to arrange that several adjacent line scans are used and these sweep the complete field of view.

In brief there are a large number of possible variations depending on:-

(1) Total Field of View required.

(2) Chosen number of optical channels.

(3) Chosen number of CGI channels.

(4) Mapping characteristic of image generator.

Fig 3 shows a typical configuration.

Despite these design choices it is likely that the major sub-systems would be very similar in each case so that:-

(1) Basically only two lasers would be required. Blue and green beams would be supplied by the argon laser and the red beam from a dye laser which will be pumped either by the blue/ green argon or by a dedicated argon laser.

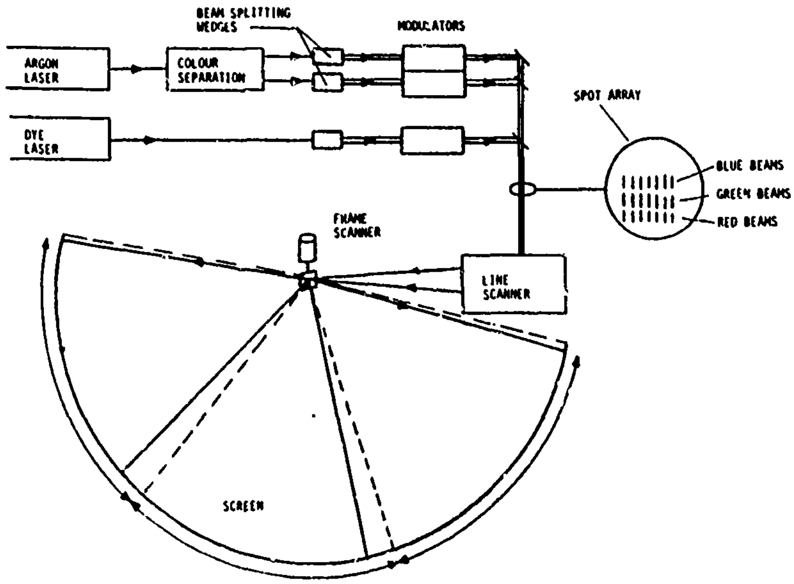

Figure 3

(2) There would be a red, green and blue acousto-optic modulator for each CGI channel. If more than three or four channels are used there would be benefit in using multi-channel modulator crystals in order to reduce complexity.

(3) All beams would be re-combined after modulation for line scanning in a single device. For the forseeable future the line scanner is most likely to be a rotating mirror polygon due to its ability to handle all colours efficiently and provide reliable operation over a long period.

(4) Frame scanning would be carried out on all line-scans simultaneously with a single device consisting most likely of a mirror, driven in a saw-tooth scan by a galvanometer.

(5) The wide-angle scene would be projected through either a single lens having a number of pupils or through a number of separate lenses.

There is potential in such a projector system for expansion, in terms of CGI channels, video bandwidths and Field of View without very far reaching changes in hardware. In addition the mirror polygon line scanner could be replaced by an acousro-optic system which would allow random scanning and raster shaping to be achieved. Also where a fixed format display was not required the projected scene could be pitched and rolled optically so as to produce an increase in the total Field of View or used for coupling to look direction.

The NTEC Helmet-Mounted Laser Projector

For applications where the instantaneous Field of View, resolution, and scene content are all required to be maximised the only practical approach is to use an Area of Interest concept. In an AOI visual system the instantaneous FOV need not extend beyond the pilots peripheral vision and the area of highest resolution and scene content is confined to a small angle corresonding to his foveal vision or look direction. Therefore, the scene content of the image is distributed much as the eye perceives the real world, thus creating the illusion of a continuous high resolution scene whilst placing an acceptable demand on the image generator and projection system.

Obviously the look direction has to be monitored by at least a head tracker, and preferably by an eye tracker as well in order that the projected FOV can be made to follow the look direction and the scene to be correctly stabilised in space.

The most fundamental consideration involved in designing an AOI visual system concerns the type of display device to be used and its location.

Clearly, there are a variety of possible approaches, including off-helmet and on-helmet CRT's and light valves, head-tracking only systems, and those incorporating eye-tracking. (Ref 4).

The display configuration chosen by NTEC (fig 4) is based on a study report carried out by Redifon Simulation Limited for American Airlines in 1979. A detailed description of the system was presented at Image II (Ref 5).

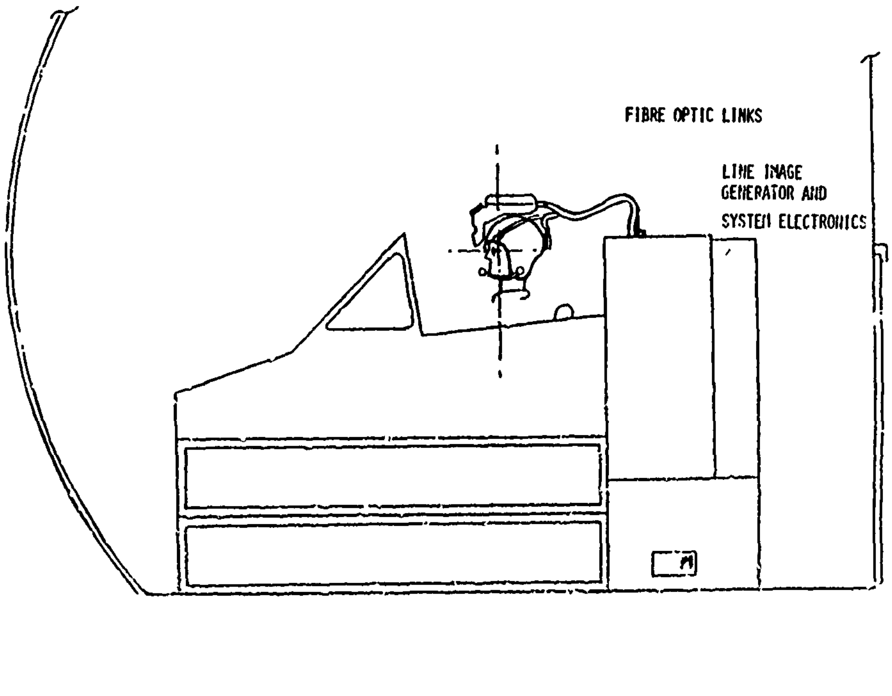

Figure 4

Broadly this concept is aimed at combining the inherent advantages of AOI with the performance potential and versatility of a scanned laser display. The system (VDRT) will be used to evaluate this concept and assess the viability of laser-based hardware in a training environment.

VDR1 Performance Specification

Total FOV	-	Limited only by cockpit structure and screen hemisphere.
Instantaneous FOV	-	140° horizontal x 100° vertical.
Area of Interest	-	27° horizontal x 24° vertical and fixed at centre of the IFOV.
Shading band	-	5° around AOI.
Apparent resolution of total FOV	-	3.3 arc mins = resolution of AOI.
Resolution of IFOV	-	13 arc mins.
Brightness	-	10 fL.
Image stability	-	throughput delay compensation by image offset using optical deflectors.

System Concept

Each displayed field will contain a nominal 1000 line raster driven by a channel of the existing VTRS image generator.

The line scans for both fields are generated remotely, off the helmet, and transmitted to the helmet via two 1000 fibre flexible links.

The line image generator assembly is shown in (Fig 5).

The helmet-mounted projector incorporates three galvanometer driven mirrors which perform frame scanning on both fields and provide for vertical and horizontal offsets of the display.

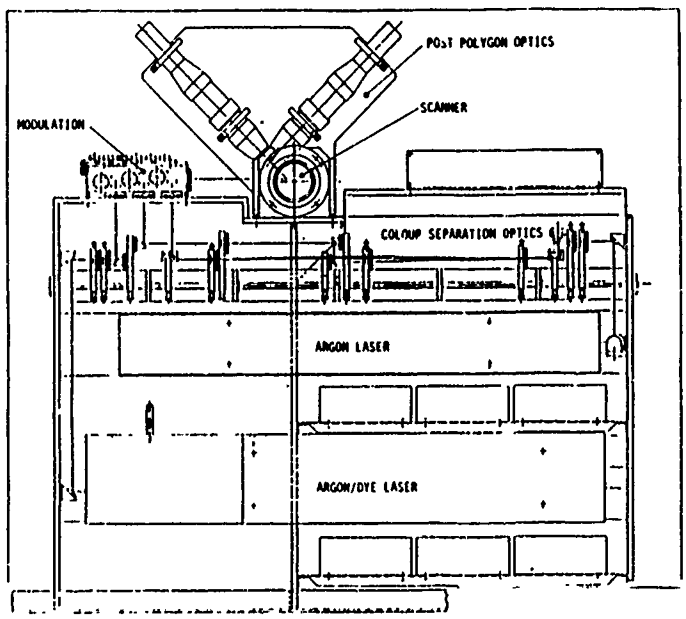

Figure 5

The AOI and IFOV fields are then combined, relayed to the single exit pupil situated approximately on the brow line and projected through a wide angle lens system.

The display screen will be the existing VTRS 10 foot radius dome which is to be coated with a retro-reflecting material.

The display will be viewed approximately 1.5° off-axis which should result in a screen gain of about 90. Reflections from within the cockpit will be very much dimmer than the screen image and should not be noticed. Window materials will, however, be removed to avoid any possible specular reflections.

System Status

NTEC awarded the prime contract for VDRT to American Airlines in October 1982, who sub-contracted the system design and integration to Rediffusion Simulation Limited. Polhemus and Applied Science Laboratories are supplying the head and eye trackers and General Electric carrying out required modifications and additions to the image generator.

System design and detailing was completed in the first quarter of 1984 with most components on order or in manufacture.

Completion and test of the major sub-assemblies, such as, the Line Image Generator, Helmet-Mounted Projector and Head and Eye Trackers is due early in the second half of 1984 with in-house inspection of the integrated laser display system occurring in January 1985.

Two separate prototype fibre optic arrays have been constructed by Galileo Electro-Optics with good results. Linearity and fibre spacing, although subject to a full evaluation, appear close to the required standard and the incidence of 'grey' fibres is fairly low. It is very probable that an acceptable fibre optic will be constructed in the next one or two attempts.

No insurmountable problems have arisen through the design phase and the system concept appears valid and able to meet performance targets.

The system is scheduled for operation on site at NTEC during the last quarter of 1985.

Summary and Conclusions

The case for using lasers to fulfill the more demanding visual display requirements of today, many of which will become standard requirements in the medium and longer term, seems most convincing on grounds of performance. The question remains as to their viability for practical operation and maintenance in the training environment.

Programmes such as VDRT will help to provide an answer.

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AD-P004 323

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Mr. Robert B. Bunker attended the University of New Mexico, receiving a B.S. in Engineering in 1948 and an M.S. in 1970. After graduation, he was employed by the Sandia Corporation as a staff member in the nuclear test instrumentation field, where he gained experience in electro-mechanical instrumentation design and testing. He also received diversified training in designing and testing rocket systems and equipment as department manager with Aerojet General and Statham Instruments, and Inter-Mountain Instruments as president and chief engineer. After joining the Air Force Special Weapons Center, Mr. Bunker received additional experience in managing the computer and data-reduction facilities and worked as a development engineer for simulated nuclear environments. While at AFHRL, Mr. Bunker has worked as branch chief of the Tactical Research Branch, assistant division chief of Technical Service Division, and as branch chief for the Technology Development Branch.

CONSIDERATIONS IN AN OPTICAL VARIABLE ACUITY DISPLAY SYSTEM

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ABSTRACT

This paper describes an effort to establish feasibility and quantify parameters of a truly optimal simulator visual system, i.e., one that fully satisfies human visual requirements with an absolute minumum of processing and display equipment. The concept is described and compared to alternate approaches with respect to size and complexity. The current effort to define parameters required to minimize potential operator distractions is described and results to date are presented.

INTRODUCTION

The technology described in this paper incorporates more than 10 years of IRAD and CRAD effort by McDonnell Aircraft Company (MCAIR).

The bulk of the previous effort was directed towards development of a remote viewing system that fully supports human vision and requires a minimum of data transfer between sensing and display locations. Original funding for development of the high risk portion of the concept, the non-linear lens, was funded by the Office of Naval Research, Reference (a). After demonstration of lens feasibility, ONR funded a brassboard demonstration system, Reference (b). Later developments, funded by the USAF and NASA, included fabrication of a small direct view display, Reference (c), a parametric study of size, Reference (d), an infrared operation study, References (e) and (f), and flight demonstration of the brassboard system, Reference (g).

Application of the concept to a simulator visual display has been under study for the last two years through MCAIR IRAD funds. Since September 1983, MCAIR has been under contract to the USAF, AFHRL, Williams AFB, for the work described in this paper.

THE WIDE FIELD OF VIEW PROJECTION PROBLEM

The requirement for realism in simulator displays has forced the designer to pursue full support of human vision in both field of view (180^{o}) and resolution (1 minute of arc). The problem encountered is depicted in Figure 1. The total number of picture elements that must be displayed is shown versus field of view and resolution. If the ultimate goal of 180^{o} field of view and 1 minute are resolution is required, about 60 million picture elements must be generated. A 1000 line television picture generates about 500,000. Thus about 100 such systems would be required to generate the desired display. Since the total system cost would be unacceptable, alternative approaches must be utilized.

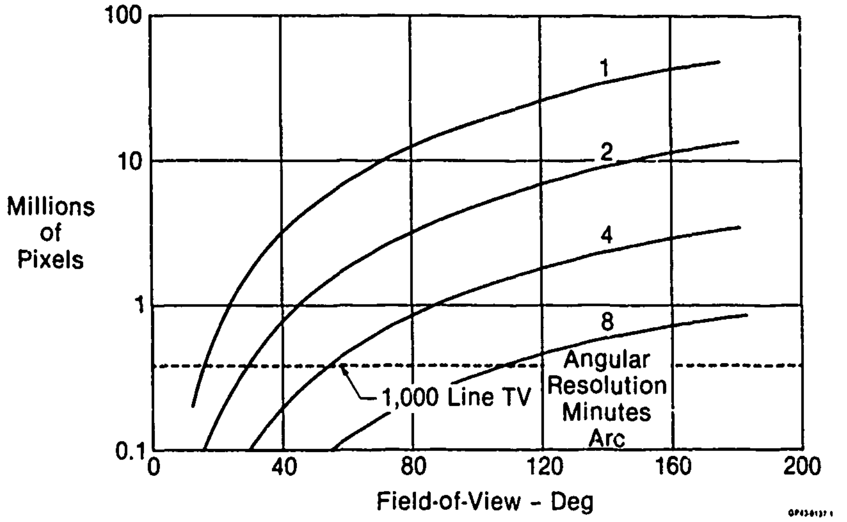


Figure 1. Pixel Requirement for Conventional Displays

The solution lies in the nature of human vision. The eye breaks its visual field into pixels of angular size that increase with view angle from its foveal axis as shown in Figure 2. This unique distribution results in a pixel count of only 200,000 - a number that could be easily generated by a 1000 line TV system and very possibly by a 525 line broadcast system.

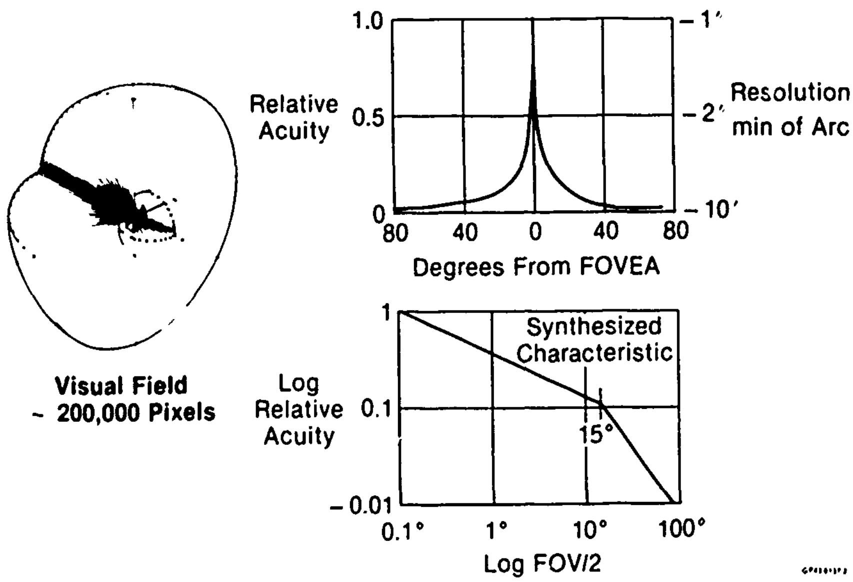


Figure 2. Human Eye Characteristic

The conventional way of approaching the solution is to use multiple fields of view - several wide ones capable of supporting human vision at the edge of a narrow field system having the desired 1 minute or arc resolution. Using 1000 line system the result is about a 40° wide field with a 10° high resolution inset. Figure 3 is an image of such a system. If this is to be a full field projection system six more wide field systems must be utilized so the narrow field can be placed at any eye view point. Design studies also show that the capability to generate two narrow fields must be available in such a system in order to accomplish the narrow field transfer across the wide field boundaries. In addition to presenting a very poor match to human vision, this approach can cause distractions due to the boundary between the high and low acuity regions.

Figure 3. Dual Field Fixed Acuity Image

A much more efficient approach utilizes a continuous distribution of the pixel size to match the eyes requirements. Figure 4 is such an image. The two approaches are compared in Figure 5. The variable acuity approach is clearly superior in every category except the positioning accuracy requirement of the narrow field region. It must be more precisely positioned in the true variable acuity system because the high acuity region is much narrower.

There are various ways to generate the variable acuity display as shown in Figure 6. On the left a linear lens is used and the required pixel size is generated by electronic means about the eye viewpoint. This approach has a problem very similar to the conventional linear approach in that the capability must exist to generate the smallest pixels anywhere on the focal plane. This means that a 1' arc capability over 180° would require a resolution across its format of:

$$N = \frac{180}{1/60} = 10{,}800 \text{ elements} \tag{1}$$

Figure 4. Variable Acuity Image

Parameter	Fixed Acuity	Variable Acuity
Acuity Match to Eye	Adequate (Too Good Over Most of Display)	Excellent
Dynamic Requirement to Reposition High Acuity Field	Moderate	Moderate - No Faster Than Fixed
Servo Positioning Accuracy Required	~ 3° - 5°	~ 1°
Projection Hardware Required	7 - 1,000 Line Dual Field Projectors (14 Light Valve Sources)	1 - 1,000 Line Video Projector (1 Light Valve)
CIG Support Requirement	9 - 1,000 Line TV Pictures	1 - 1,000 Line TV Pictures
— Total Pixels Generated	4,500,000	500,000
— Pixel Generation for Viewpoint Change	1,000,000	500,000
Physchophysical Concerns	Distracting Transition at Edge of High Acuity Field	Discussed on Later Chart
Reliability - MTBF	A	~ 14A

Figure 5. Comparison of Dual Field Fixed Acuity System to a Variable Acuity System

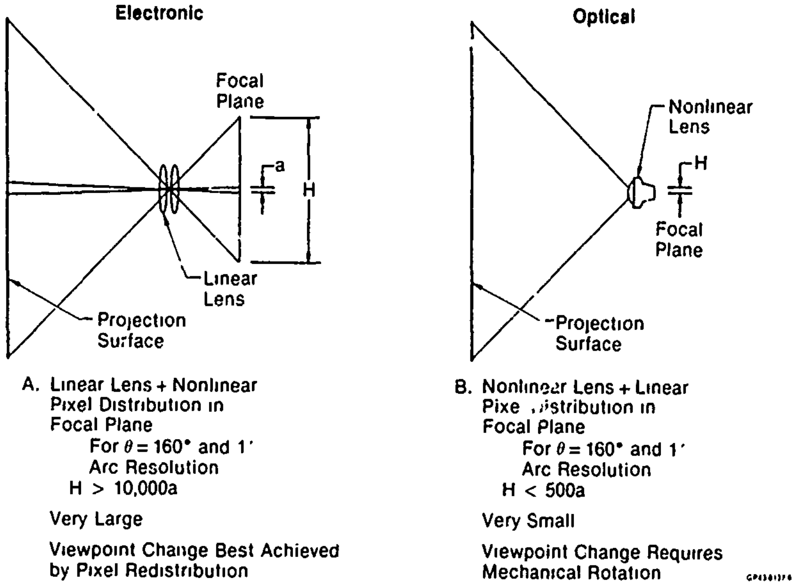


Figure 6. Ways of Generating a Variable Acuity Display

Such a capability would require an array of ten by ten 1000 line state of the art projection systems to support the concept even though only one would be required to produce this resolution at any particular time.

PROPOSED SOLUTION

Another approach pioneered by McDonnell Aircraft Company, is to utilize a special non-linear lens which has a focal length that varies with field angle in the same function as eye acuity. This lens will then project a uniform pixel density in its focal plane onto a screen with variable angular increments exactly as required for full support of human vision. In this approach the lens must be mechanically rotated in two axes so its optical axis always falls on the eye viewpoint on the projection screen.

The prototype MCAIR non-lienar lens, shown in Figure 7, was made rather large for ease of construction. It is about 8" in diameter and 8" long. Design studies show it can easily be reduced to 1/2 this size. The characteristics of this lens can be shown by comparing its focal plane image to that of a fish-eye lens covering the same field of view, Figure 8. Note that the buildings that occupy over half the format of the non-linear lens are so small they can barely be discerned in the fish-eye image. This illustrates the unique characteristics of the non-linear lens which behaves like a long focal length (telephoto) lens near the optical axis and a very short focal length (wide angle) lens at the field edge.

A possible hardware arrangement for a variable acuity projector utilizing the non-linear lens is shown in Figure 9. Here a light valve projector is coupled to the lens via a fiber optics relay. A high intensity CRT is also being considered for the source which could be placed directly in the focal plane of the lens.

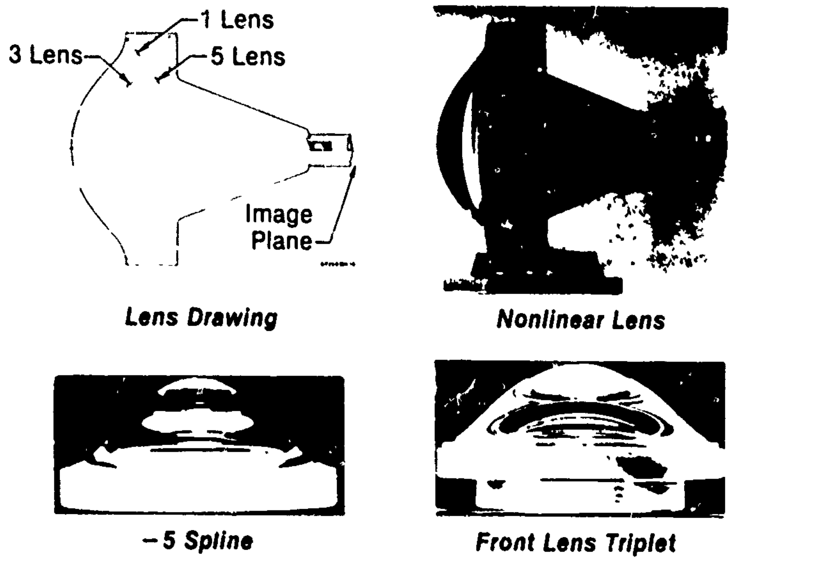
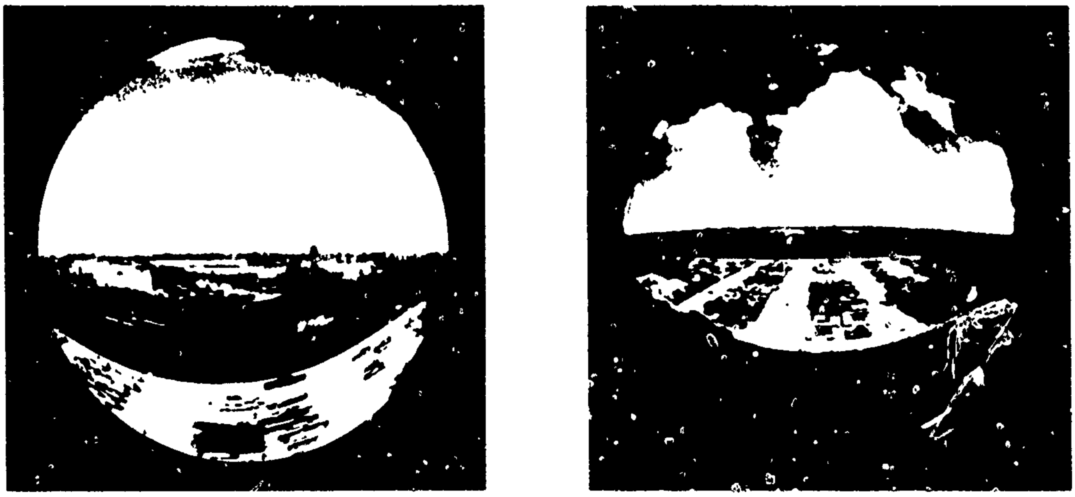


Figure 7. The Prototype MCAIR Nonlinear Lens



Nonlinear Lens Image ***Fisheye Image***

Figure 8. Comparison of Nonlinear Lens Image to a "Fish Eye" Lens Image GP43 0137 11

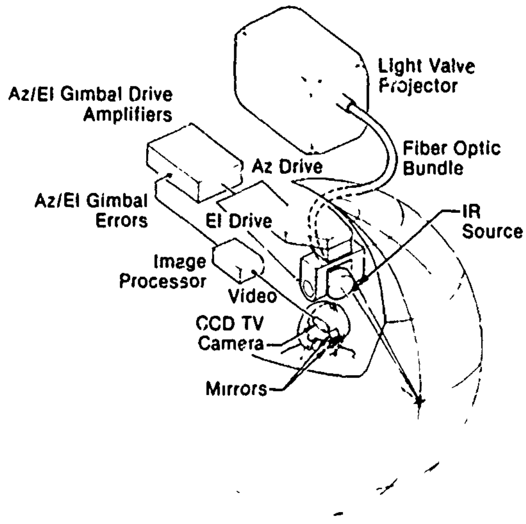


Figure 9. Variable Acuity Simulator Concept

The potential hardware advantages of the non-linear lens approach to variable acuity projection are illustrated in Figure 10.

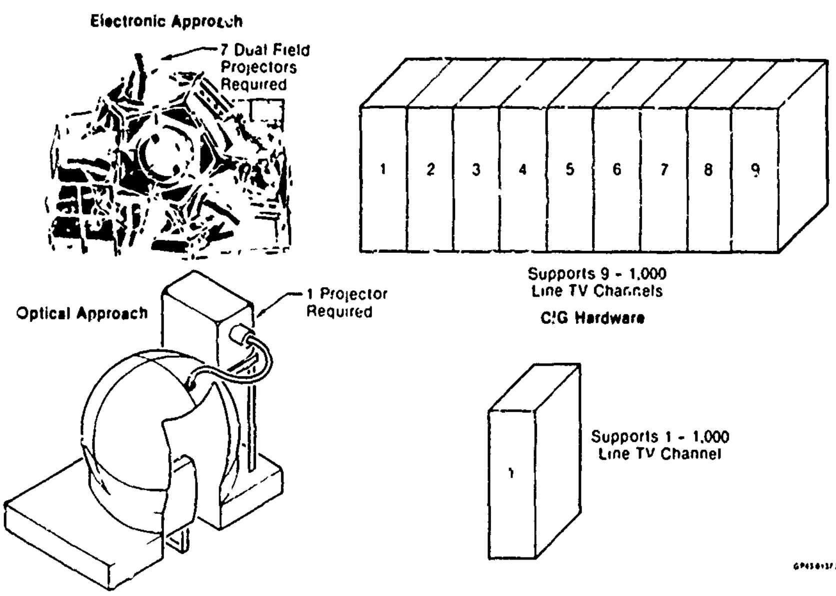


Figure 10. Hardware Comparisons for Equal Visual Capabilities

TECHNICAL CONCERNS

There are several concerns with this approach that must be resolved before its feasibility can be proven. They include:

1. The effects on display quality of display persistence, frame or CIG delays, servomechanism dynamic response, and adequacy of the eye sensing and control system to properly position the variable acuity field.

2. Computer Generation of the required non-linear image.

Both of these items are presently under study, but this paper addresses only the first.

EXPERIMENT DESCRIPTION

Literature surveys were of very little help in resolving the concerns. After an extensive study the experimental hardware shown functionally in Figure 11, was devised. The actual hardware is shown in Figure 12. Two diametrically opposite screens were constructed. The one on the left is used for stimulus projection from a slide projector whose optical path is deflected by a servo driven mirror. This hardware can be seen in Figure 12 at the top of the close-up photo. The stimulus position is viewed by the TV camera whose field of view is positioned by another servo driven mirror (the lower mirror on Figure 12). The projectors field of view reflects off the back of the camera mirror and is projected on the right screen. This causes the camera and projector fields of view to move in unison and with perfect registration. By connecting the camera video to the projector, the observer viewing the projected image sees the exact spatial detail that exists on the other stimulus screen. This observed image is degraded by the system parameters of servo response, display persistence, camera lag, camera integration time, and video frame lag exactly as they would occur in the variable acuity remote viewing concept. In addition the acceptability of the acuity fall-off function can be evaluated during testing by placing a non-linear spatial filter in the camera aperture.

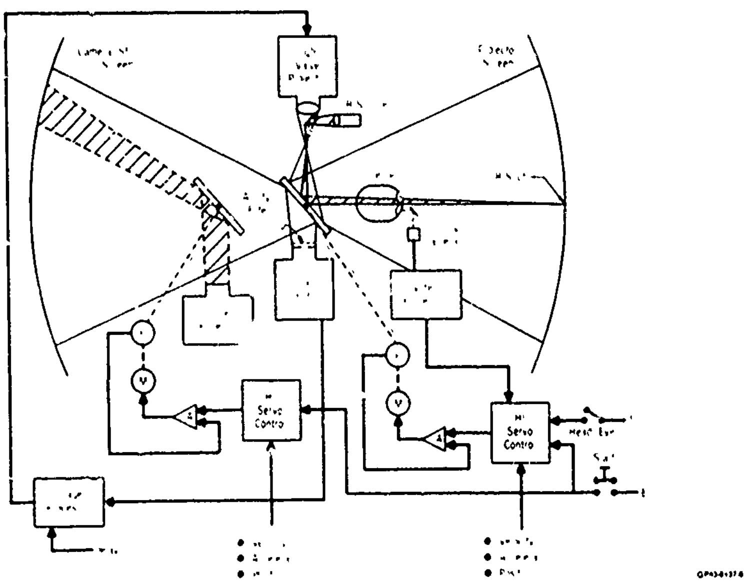


Figure 11. Equipment Functional Diagram

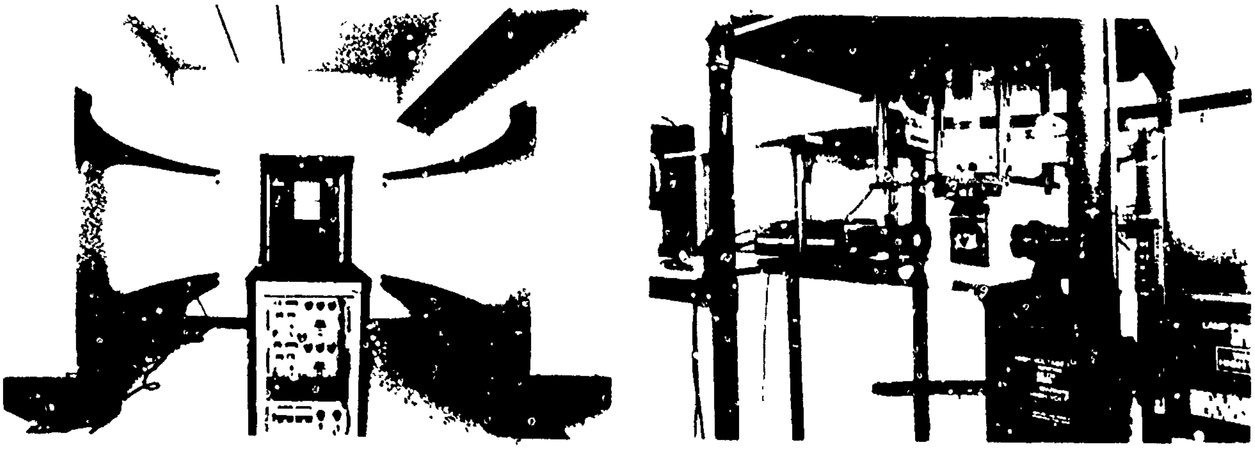


Figure 12. RD-2 Experiment Hardware

GP43 0137 12

Evaluation of the simulator application, where the video is computer generated, will require replacement of the camera in the experiment with computer image generation of the stimulus. In this case the stimulus deflection and compensating effects of projector mirror rotation will be accomplished electronically. Variable acuity will also be accomplished electronically in this case. Eye sight line position is measured by a helmet mounted TV camera which views the eye's cornea spot relative to the pupil iris boundary. The corneal spot is generated by an infrared spot which is projected along the projectors optical axis location on the viewing screen as shown in Figures 9 and 11. This approach has the advantage of being a "null balance" system, i.e. the error is zero when pointing is correct. Eye position error signals are processed by the HI servo controller algorithm for filtering of unwanted eye motions.

As of this date only the TV camera approach has been implemented without eye control. Nevertheless, some very interesting results have been obtained. These tests consist of allowing the observer to view the projection of the stimulus as it moves from one point to another in a very short period of time (about 10 ms). The camera and projector servo is started at the same instant. Dynamic response is gradually increased and threshold acuity measured by the observer for each test run.

RESULTS

The results are shown in Figure 13. At zero response the system is static and the observer sees the inherent video system resolution. When the servo is allowed to follow the stimulus, degradation in acuity is immediately observed - even at rates as low as 2°/sec. Degradation continues to increase as servo response is increased until about 160°/sec where an improvement begins. By running the experiment for different angular deflections we can

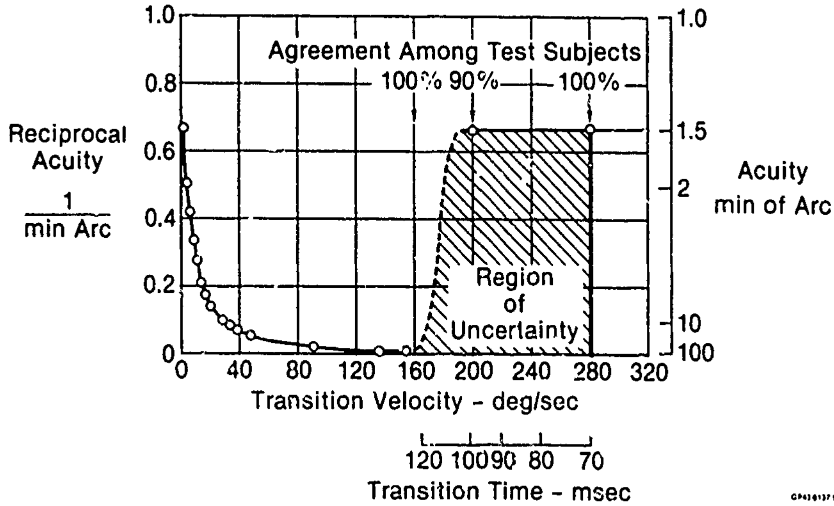


Figure 13. Preliminary Test Results
20° Stimulus Deflection RD-2 Hardware

show that the overall transit time is the controlling parameter in this region rather than velocity. The transit time is in the area of about 120 milliseconds at this point. Different observers disagree exactly where performance returns to its static value but 90% of them can see no degradation when the servo transit time is about 100 ms. Some observers insist they can see degration until transit time is in the area of 70 ms.

Figure 14 shows how a 100 ms servo transit time contributes to a stable image. Note that the total time to a stable image is the sum of the servo transit time plus at least one frame time and the projector's persistence interval. For the hardware used in the experiment this additional time is about 40 ms. Future tests will establish the exact contribution of each of these.

Figure 14 suggests that the CIG interval could be increased considerably beyond the frame time by using a prediction algorithm to anticipate where the new eye point will be. Theoretically this could be done after the eye has reached its stable position, a relatively short time, as illustrated in Figure 14. This could make the CIG interval almost as long as the servo transit time. This hypothesis will also be verified in future tests.

SUMMARY AND CONCLUSION

Results to date indicate psychophysical problems caused by servo transit time, frame time, and persistence can be avoided if the sum of these times is less than 140 ms. This is a reasonable value and well within the state of the art.

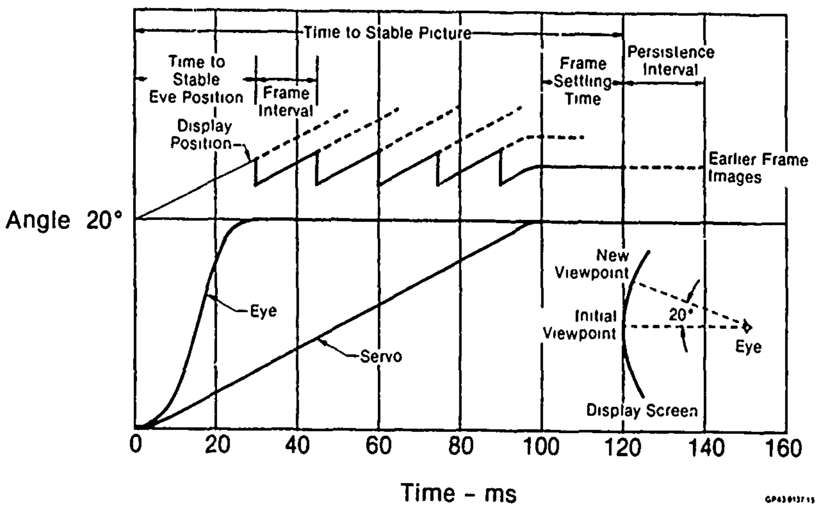


Figure 14. Events for 20° Shift in Eye Position
Conditions for No Observed Degradation -
90% of Viewers

By the time of paper presentation the effects of frame delay and persistence should be established. The ultimate verification of the concept using eye control should also be well underway. These results will be presented at that time.

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SESSION V

Display Considerations
Part II

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LtCol Jenks has earned a Master of Science Degree in Aerospace Management from the University of Southern California, and graduated from the Command and General Staff Course at Ft. Leavenworth, KS. He is a member of the Army Aviation Association of America, the American Helicopter Society and the Society of Experimental Test Pilots.

DESIGN CONSIDERATIONS FOR AN EYE TRACKED AOI DISPLAY SYSTEM

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DESIGN CONSIDERATIONS FOR AN EYE TRACKED AOI DISPLAY SYSTEM

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ABSTRACT

The potential benefits of using an Area of Interest (AOI) display for high performance out-the-window visual simulation is evidenced by the current activity in this display technology. The AOI concept can be implemented in many versions. In each AOI display type a complex tradeoff of performance parameters must be considered. A review of these considerations will be discussed in this paper concentrating upon the display versus the CIG. The display being developed for the Visual System Component Development Program (VSCDP) by the General Electric Company (GE) is an AOI display concept. The major features of the display system and the current status of the display development will be discussed.

INTRODUCTION

The gains to be made in cost improvements and performance for an Area of Interest (AOI) display concept have been investigated and reported on extensively in the simulation community. Various display configurations that provide approaches to the AOI concept have also been proposed and are in various stages of development. The purpose of this paper is to give a brief summary of some of the work that has been done, discuss the considerations in the design of an AOI display, and to describe an AOI display that is currently under development for a helicopter visual system under the GE VSCDP program.

The AOI concept is based upon providing the observer a limited field of view that tracks the portion of the out-the-window scene upon which the trainee is concentrating his attention. Since this portion of the scene is typically a target, one could think of a class of AOI display that operates in a "target tracked" mode. This approach is limited in that a separate display/image source must be provided for each target. A second class of AOI display is one in which the tracked portion of the scene is coupled to the head motion of the trainee. Still another class is one in which the tracked scene is selected based upon where the gaze of the trainee, that is the foveal region of the eye, is directed. This third class of AOI displays offers the most potential in the cost/performance tradeoff while presenting the greatest challenge to implement. The subject of this paper is the latter two classes in which the pschophysical aspects of the head and/or eye motions of the trainee are important considerations.

BACKGROUND

The development of various AOI displays is summarized in reference 1 which discusses the "trend toward Area of Interest" display technology in the simulation industry to solve the field of view/resolution tradeoff in the higher performance trainers. Four of these fall into the head/eye tracked AOI display type that is the subject of this paper. Of these four, two are helmet mounted displays [2-4] and two utilize servos for positioning of the AOI [5,6].

The two helmet mounted displays (HMD) are each unique approaches to solving the AOI display problem. The laser scanned design [2,3] is one in which an off-platform line scanner feeds the helmet mounted portion of the display via a fiber optic ribbon. The scan lines are then frame scanned with a galvanometer mounted on the helmet and projected to a dome through a projection lens. The galvanometers on the helmet are also capable of offsetting the raster to account for eye eccentricities with respect to the helmet. A more important role of the offset is to account for the fact that the transport delay of the various display components (eye/head tracker sensor and computation system and the CIG) results in the helmet, and therefore the projection system, being moved from the position at which the scene was computed.

The second HMD [4] is a virtual image system. The current configuration provides for an offset of both the inset and the background imagery. The offset is achieved optically by physically displacing the fiber-optic bundle. This approach, while being straightforward, can be used for only small angles before the errors introduced by decentering the CIG computational tangent plane and the optical system tangent plane become appreciable. Extension of the display concept to allow for eye tracking of the center of the AOI, with the larger angles involved, would impact the CIG. This display is currently at AFHRL, Williams AFB, Arizona being evaluated. In both of the HMD concepts there is a means for coping with the problem of coordinating the imagery as computed with the position of the display when the video is actually being output which are in general not equal to each other.

The servo approach to the AOI display offers an added degree of freedom, that is, the decoupling of the head from the display. This allows the display designer a wide range of strategies for controlling the coordination of the display positioning and the CIG computed position. The ASPT-HRA (High Resolution Area) [5] display was developed as a research tool to provide a wide variety of test configurations. The display can operate in either a head coupled mode or a target tracked mode. The AOI of the display is inset within the static 90 degree field of view background scene and the transition between the AOI and the background is achieved electronically. The CIG with which the HRA is currently operating is a 30 hertz update system and consequently the display is best used in the target tracked mode. The TCT/EDIT display [6] is a real image dome display in which the AOI portion of the scene is servo positioned and superimposed upon or inset within the static

background imagery. The wide range of field of view coverage for the AOI center requires that there be two AOI projectors with a coordinated passoff region. This display is a true eye/head directed AOI display.

There are many possible configurations for implementing an eye/head tracked AOI display system. Of the examples that have been briefly discussed here, each has its own set of benefits, compromises, and disadvantages. The features that should be addressed in the design of such a system are the same as would be applicable for any conventional display as well as a set that is unique to this class of display. Some of the major questions that must be addressed that are applicable for AOI displays are:

1. What is the observer (pilot) acceptability of the display from the standpoint of increased inertia and weight to the helmet?
2. Is the display to be head or eye directed?
3. What is the field of view/resolution of the AOI?
4. What is the field of view/resolution of the BG?
5. Are the standard display performance parameters acceptable (eg. luminance, contrast, resolution, etc.)?
6. What is the minimum accomodation distance of a real image display?
7. What can be done to minimize the artifacts at the AOI/BG boundary?
8. Does the display compromise instrument or avionic visibility?
9. How does the display cost compare with that of the CIG channels that were eliminated with the concept?
10. Is there a viable means for coping with the transport delay of the various components of the visual system?
11. Does the display simulate the obscuring effects of canopy struts etc.?
12. Is safety considered?
13. Is the binocular cue provided by the concept?
14. What is the impact of the display concept on the CIG?

The best AOI display will be the optimal tradeoff in answering these questions.

EYE/HEAD CHARACTERISTICS

The characteristics of the head and eye motions are discussed in several places in the literature [7,8]. Some of the pschophysical effects of the visual system are also discussed that are of interest in the design of an AOI display [6]. While it is not the intent of this paper to deal with this subject extensively, some mention should be made of major considerations.

Although the eye can percieve imagery over a large field of view, high acuity is achieved only within an area that subtends several degrees called the fovea. The resolution of the eye falls off very rapidly as a function of field angle from the fovea. The remainder

of the field of view that the eye can see, the peripheral field of view, is much lower resolution; however, edges and motion in the periphery are easily percieved. The eye therefore must scan its large instantaneous field of view using saccadic eye motions and then fixate upon targets of interest. This saccade-fixate pattern of eye motion is typical and can be continual for certain scenerios. Saccadic eye motions are characterized by very high accelerations and velocities and are of short duration. Fixations are of a duration typically greater than 200 milliseconds. Another eye motion that is common is termed smooth pursuit. This type of motion is used for following targets that are moving with respect to the observer. A third type of eye motion that should also be considered in the design of an AOI display is the vestibulo-ocular eye motion. This eye motion is the reaction of the eye to head motion that is opposite to the head motion. Of the eye motions that have been briefly discussed the saccadic eye motions are the most demanding from the point of view of the design of an eye tracked AOI display.

Coordinated eye and head motions are also used to position imagery upon the foveal high resolution region of the eye for discrimination tasks. The eye typically rapidly moves to a new position with a saccadic eye motion and then the head follows so as to end the coordinated eye/head motion with the scene of interest nominally straight ahead with respect to the head. This pattern appears to be typical because it is fatiguing to maintain an eccentric eye angle for an extended time.

In addition to the motion characteristics of the eye there is a phenomenon called saccadic suppression [7] that prevents streaking of imagery across the retina during a saccade. This phenomenon is not completely understood but the effect is that the visual threshold is reduced just prior, during, and immediately after a saccade. It is apparent that saccadic suppression is an effect that can and should be exploited in the implementation of an AOI display.

In addition to the research that is being done on eye/head motions and the psychophysiology of visual perception, there is also work that is directly applicable to defining the desired chacteristics of AOI dispays [8]. Research that may prove to be of value in eye/head directed AOI display systems involves prediction techniques. There has been work done in prediction of eye [9] as well as head motions. Although these schemes have not been implemented to the knowledge of the author, the potential benefits of accurate predictions of head and eye position are obvious.

THE GENERAL ELECTRIC VSCDP DISPLAY CONCEPT

General Electric Company is currently under contract for an advanced visual system for the AH-64 helicopter. The program is called VSCDP, the Visual System Component Development Program. The VSCDP display system is an Area of Interest display system that is a unique combination of AOI display characteristics and also employs several novel features (patent applied for). An artist's concept of the display concept for VSCDP display is shown in figure 1 and a block diagram of the display system is shown in figure 2. The VSCDP

display is a real image dome display concept that utilizes a servo for positioning of the AOI. This Servo Optical Component (SOC) optically combines the AOI and BG imagery and projects this composite imagery through a common optical system that is integrated with a two axis elevation over azimuth gimbal. The AOI and BG scenes therefore are concentric and remain in this relative orientation for all servo positions. This allows the AOI and BG imagery to be aligned initially optically and this registration does not change. This fixed relationship between the AOI and BG imagery also allows the transition region between the AOI and BG to be blended smoothly and continuously with complementary optical blend filters. In this way the registration and AOI/BG transition problems associated with other AOI display concepts are solved.

The positioning of this AOI/BG imagery is directed by the trainee's gaze such that the foveal position of the eye is located within the AOI. The gaze position is determined with an Eye/Head Tracker System (EHTS) that is helmet mounted. The device developed by Honeywell Avionics Division under the TCT program [6] and improved under the VSCDP program adds very little inertia to the trainee's helmet. The EHTS output provides helmet position and angular attitudes, eye line of sight angles with respect to the helmet and, the vectorial sum of the helmet plus the eye line of sight. The output of the EHTS is updated at a 60 hertz (field) rate and the transport delay is between 2 and 3 fields depending upon the saccadic magnitude.

The heart of the VSCDP diplay system is the display computer (see figure 2). The gaze position output of the EHTS is input to the display computer (DC) and the DC performs several very important functions that are essential to the successful implementation of the VSDCP diplay concept. The EHTS data is compared with previous gaze data and various functions are performed before the DC provides an output to the CIG and the SOC. The DC provides deadband and rate limiting functions. The former functions to filter the EHTS data to ignore the noise of the EHTS and the involuntary microsaccades of the observer. The later provides the capability to control the maximum angular step of the CIG/SOC per field. Next a CIG view window definition is input to the image generator so that the video image computation cycle can begin. This view window definition is computed based upon gaze point data and a mathematical estimator which predicts the dynamic response of the SOC gimbals to an input step. The angular transformations from observer to SOC gimbal space are performed next. The SOC input is then appropriately delayed so that the gimbal motion is coordinated with the video output of the CIG.

The performance of the Servo Optical Component (SOC) is crucial to the success of the VSCDP display system. The SOC is a device, being developed by Contraves Goerz Corporation, that integrates optical and servomechanical technologies. Imagery from the AOI and BG (background) light valves is relayed at different magnifications to separate intermediate image planes. At each of these planes complementary gradient filters are placed to produce the AOI/BG transition functions. These two images are combined with a

beamsplitter, the composite image passing through an optical derotation device, and a common objective lens that is servo driven.

The AOI video source is a commercially available model PJ-5155 color Schlieren light valve manufactured by the General Electric Company. The background display source is an arrangement of dual GE light valves. The display source for the BG channel is a combination of two GE light projectors that are combined in this application to achieve greater luminance. This is neccessary because of the large difference in the magnifications of the AOI and the BG optical paths. The result of this configuration is that the BG luminance can be substantially increased thereby increasing the luminance of the entire display system since the AOI and BG luminances are equal.

The system performance of the GE VSCDP display system is summarized in table 1. The display system is one which includes many of the best features of the AOI concept. The display adds very little inertia or weight to the trainee's helmet. The only additional helmet mounted components are the components of the EHTS which weigh less than 0.3 pounds. The display will be relatively free of artifacts at the AOI/BG boundary because the AOI and BG are registered with respect to each other and the AOI/BG transition are optically blended to provide the best possible transition.

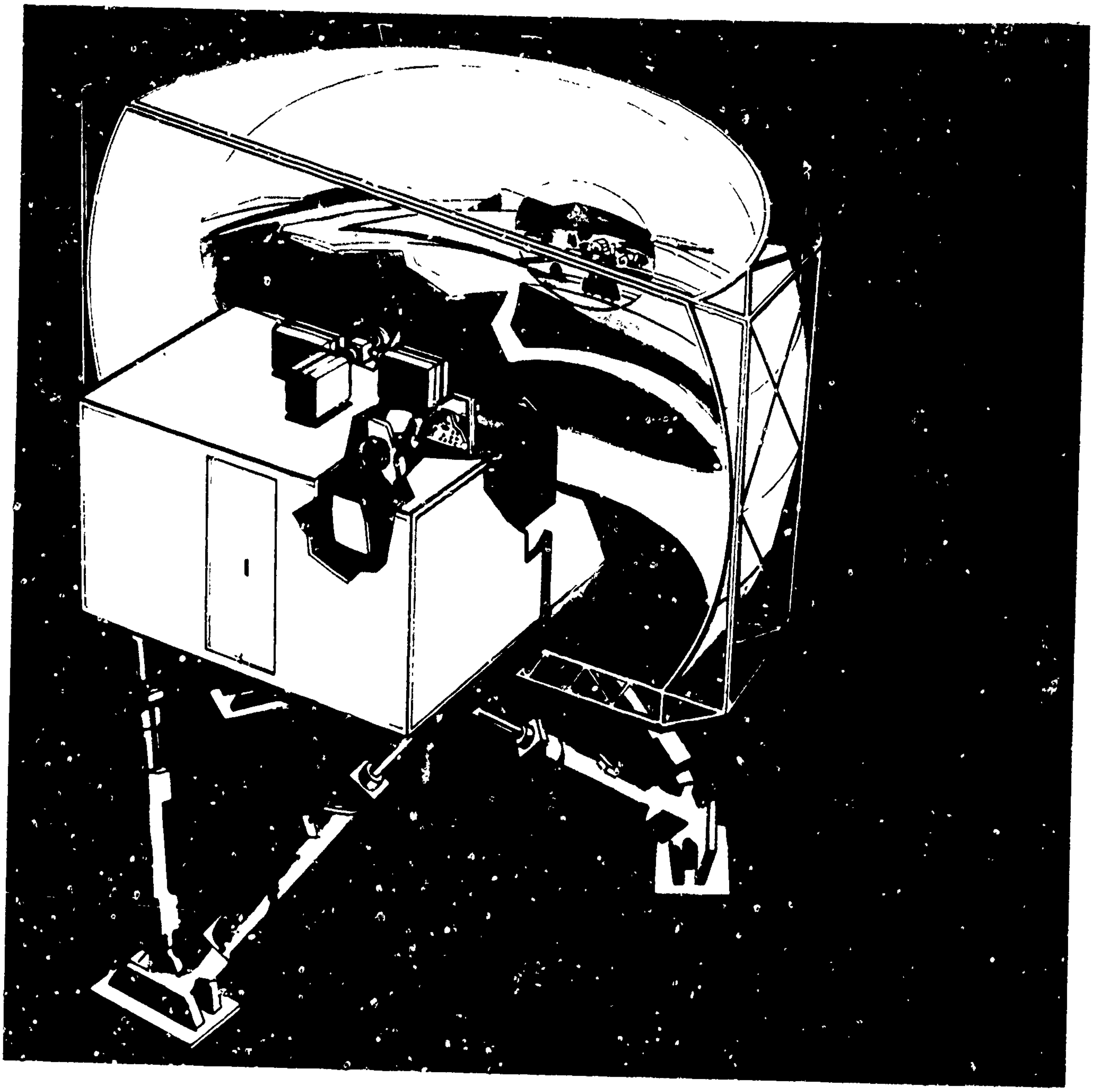
The dynamic performance of the entire display system is being analyzed with a simulation program until the hardware is available. The program, the Control Systems Analysis Program (CSAP), considers the dynamic response of the display system components (EHTS, SOC, DC, and the CIG) including the transport delays. For a given gaze profile (which is a data base that is the input to CSAP) the program can evaluate several attributes. The program analyzes the errors between the CIG computation position and the SOC position when the video is being output. This error, termed type I, is a measure of how well the CIG and the SOC are coordinated. A second error that is measured, the type II error, is the error between the gaze point and the position of the SOC. This error is a measure of the degree to which the SOC is able to keep up with the observers gaze. Other dynamic effects are also evaluated including the image artifacts that occur due to the motion of the SOC during the output of a field of video imagery. The CSAP is a tool to determine the quality of the display system and the effect of parametric changes to the system.

The VSCDP Phase II contract was awarded to GE in April 1983. All major subcontracts for the Display system have been awarded and the development efforts are on schedule. The integration of the VSCDP display will be completed at AFHRL, Williams Air Force Base, Arizona in the fourth quarter of 1984.

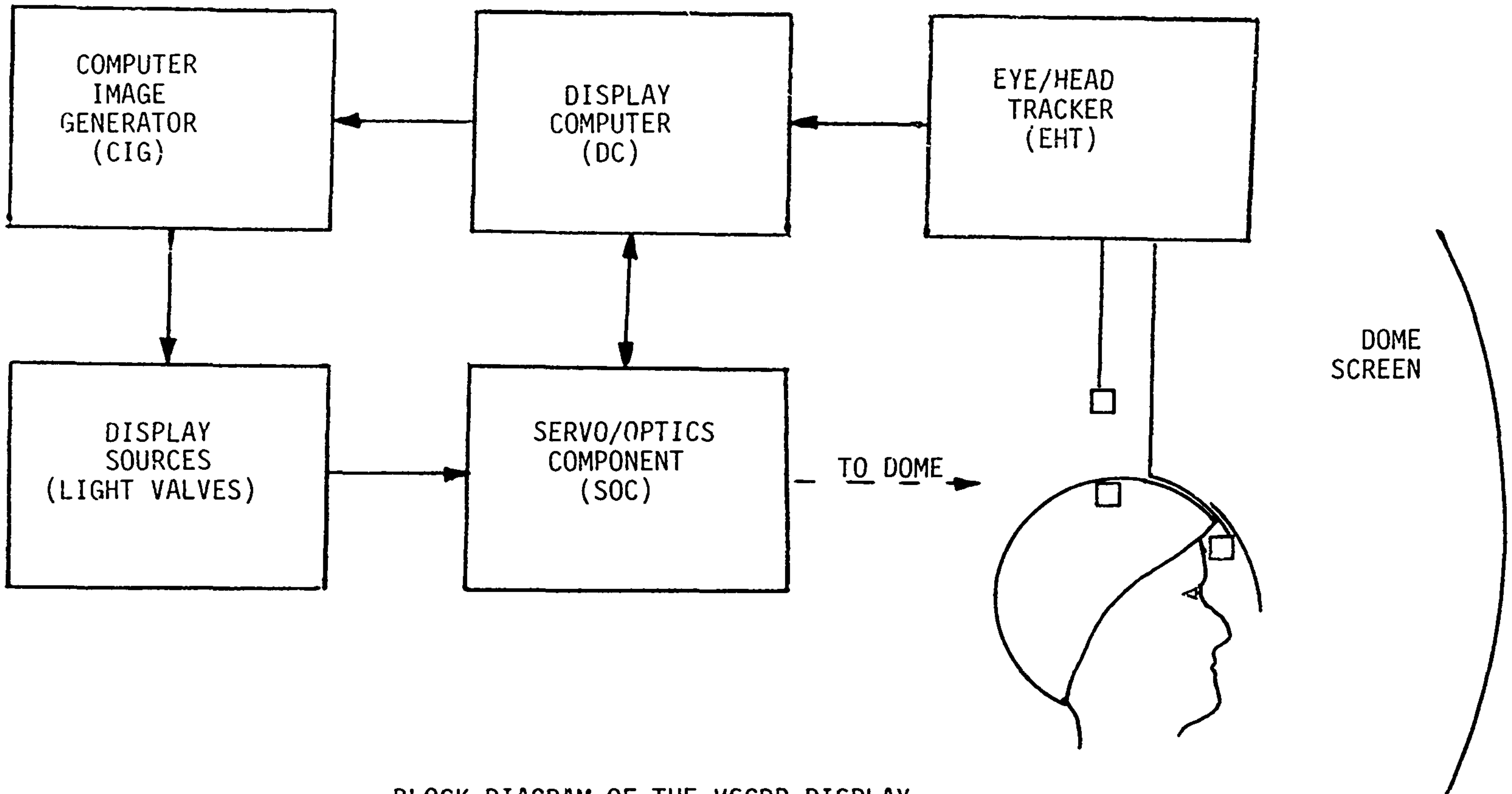
SUMMARY

This paper has summarized various AOI display technologies that are currently being developed in the simulation community. The characteristics of eye motions have been discussed and references noted. Finally the GE VSCDP display system has been described. It

is felt that this display system is a new approach to effectively providing AOI imagery. It is anticipated that the VSCDP display will be a major contribution to the development of AOI technology that promises to provide high performance visual simulation at a lower cost.



ARTIST CONCEPT OF THE VSCDP DISPLAY
FIGURE 1



BLOCK DIAGRAM OF THE VSCDP DISPLAY
FIGURE 2

Table 1
Performance of the VSCDP Display System

	Performance Requirement	Predicted Performance
1.	Field of View/Resolution (minimizes periferal miscues, approach the resolution of the eye)	met
2.	Servo Dynamic Performance (approach that of the eye)	met
3.	Field of Regard of Center of AOI/BG (Az +/- 90, El +/- 40 degrees)	met (not limited by SOC range)
4.	Luminance	4.0 foot Lamberts
5.	Dome Diameter	24.0 feet
6.	Optical Blending Transition	5.0 degrees
7.	Number of CIG channels	2
8.	Weight added to the helmet	0.3 pounds

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Control Systems Analysis Program :
A Tool for Analysis of the GE-VSCDP
Image Display System

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Control Systems Analysis Program :
A Tool for Analysis of the GE-VSCDP Image Display System

ABSTRACT

CSAP is a simulation program used to analyze the performance of the GE-VSCDP image display system. It has been used to define some unknowns and to analyze the AOI/BG image's shear effect and dynamic distortion due to finite servo velocity. Of major importance, it is used to optimize the image display system to minimize the displacement error between the center of CIG image and the center of the servo projector.

1. INTRODUCTION

There is an increased reliance on simulators for training tasks for fixed-wing aircraft as well as helicopters. Cockpits in these aircrafts have improved visibility, which requires greater fields of view (FOV) for the simulator's visual system. Better resolution is also required for low-level aircraft missions to provide tree-top tactical and navigational cues. As a result more demands are being placed on a visual display system which can provide high resolution and wide FOV.

One currently available approach to providing the required high resolution, wide FOV display is to divide the FOV between a number of juxtaposed channels surrounding the pilot. But the cost of such a system is high. As an alternative to generating and displaying imagery over the full FOV required by the pilot, imagery can be concentrated in the Area of Interest (AOI) that is most useful to him, resulting in significant cost savings in both image generation and display hardware. Spooner(1) described the types of AOI display systems currently in development which are target-tracked, head-tracked, and eye-tracked AOI display systems. An integrated eye/head-tracked AOI visual system has not been demonstrated at this time.

For the Visual System Component Display Program (VSCDP), General Electric Company has selected a display system which utilizes two CIG display channels; one provides the background (BG) image and the other provides the AOI image. The AOI image has a higher resolution than the BG image. The BG and AOI are always centered with respect to each other; both are slewed together to provide a wide FOV coverage with a central higher resolution area. Since both AOI and BG are fixed with respect to each other, the dynamic problems of insetting are eliminated. The AOI is optically inset so that a truly smooth image transition is achieved, avciding the quantization problems associated with the digital electronic insetting concepts. This progressive display design offers a

relatively inexpensive visual simulation approach that provides wide FOV imagery, high resolution AOI and is uniquely capable of solving the insetting problems. One other feature is that this display system is an eye/head-tracked AOI system.

The principal components of this visual simulation system are the Eye/Head Tracker (EHT) which provides the eye/head position and the gaze direction, a CIG which generates a picture for a defined view point and gaze direction, the Servo-Optical Projection System (SOPS) which slews the CIG picture on a dome screen, and a display computer (DC) which controls the data flow and timing such that the SOPS can slew the CIG picture to where a pilot is looking. A sophisticated software analysis package which is called the Control Systems Analysis Program (CSAP) has been created that emulates the GE-VSCDP visual system and has been used as an analysis and design tool during system development.

2. GENERAL DESCRIPTION OF CSAP

Figure 1 shows the simplified block diagram of the VSCDP visual system. The EHT detects a pilot's eye position and gaze direction which are input to the DC. The DC uses the eye/head data to test if the pilot is looking at a new point. If this is the case, DC directs the CIG to compute its next field of data for a view point and also directs the SOPS to slew this new picture toward this point.

Each of these four components has a transport delay. The EHT transport delay plus that of TP is 50 ms, the CIG delay is 50 ms, and that of SOPS is so small as to be neglegible. The total delay is 100 ms. The timing diagram shown in Figure 2 describes these delays. Each tic means one field time(1/60 sec). This timing diagram depicts the potential problems caused by these delays. The motivation for developing this program is to solve the problems associated with this transport delay and servo response.

In the DC, there is a sophisticated algorithm which makes the DC properly control the data flow and timing. With the eye point and gaze direction, this algorithm can indicate if a pilot is looking within the area which is blocked by the cockpit, if the SOPS needs to slew the picture, and how far and when the SOPS should slew the picture.

The human eye is constantly changing its position by up to several degrees due to involuntary microsaccades during fixated observation. In order to limit the movement of the CIG image during these very small eye movements, a variable called Dead Band (DB) was defined in the CSAP. In addition, the Angular Threshold Value (ATV) was defined to limit the maximal allowable slewing angle per system sample period. By executing this program, both variables can be defined easily.

Two different type errors were defined in the CSAP. The first one is the type I error which is the difference between the CIG image center and the SOPS center during and immediately following gaze angle changes. The second error is called the Type II Error which is the difference between the gaze point and the AOI center. In the next section, the efforts for reducing the type I and II errors are discussed.

In order to include the effect of the servo dynamics, its math model has been implemented in the CSAP. The servo system consists of two subsystems; an analog control and a torque motor. Figure 3 illustrates a block diagram of the general servo system. As can be seen from this figure, the servo system consists of three main feedback control loops: the position control loop, the speed control loop, and the acceleration control loop.

The system receives a position control signal which is then transfered into an angular velocity control signal through the nonlinear function (see Figure 3); this forces the torque motor to reach the positon demanded at the highest angular velocity. The acceleration feedback loop forces the system to reach the maximum angular velocity at the maximum possible motor acceleration. In order to obtain a good steady state accuracy, the controller switches to a position control when the servo position is within one degree of the position demand.

There are two data input files for the CSAP simulation program; one provides all of the variables (DB,ATV,etc) and the other provides a set of coordinates of gaze points for each field . With this data, the CSAP can compute and plot type I and type II errors versus time and their RMS values and their peak errors. CSAP can plot the gaze point, the CIG computation center, and the servo projection center for each field in a FOV plot; it can also plot the AOI profile from which the shear effects caused by servo motion in each field can be analyzed.

3. RESULTS AND ANALYSES

Once the CSAP was developed, various sets of the data were analyzed. As will be illustrated in the following paragraphs, the CSAP helped to explain and understand the effects of the key parameters on the VSCDP. The study focused on limiting and reducing the type I and II errors. Figure 4 shows some typical results of the type I and II errors at various values of DB and ATV derived during the course of system design. Figure 4(a) shows the curves of RMS value of type I error versus the ATV if the DB is changed from 1 to 3 degrees; this figure indicates that RMS values of type I error will increase if DB increases. Figure 4(b) shows the curves of RMS value of type II error versus the ATV if the DB changes from 1 to 3 degrees; this figure illustrates that RMS of type II error will approach an asymptote if the ATV increases. With these two figures, it is apparent that the ATV should be greater than 4 degrees and the DB should not be larger than 2 degrees. Figure 5 shows the FOV

plots of a rectangular AOI image as it is distorted during very rapid gaze point translations. As can be seen from the plots, in the nth field, the gaze point has just changed to a point which is outside the AOI coverage. In the (n+1)th field, the SOPS starts to slew the CIG image toward the current gaze point. Because of this slewing, the AOI profile is distorted and a line oriented in a direction perpendicular to the velocity vector can appear to be broken into three segments. However, this broken line effect is significant only during rapid slewing rates when the observer's visual acuity is reduced.

Figure 6 shows the result for type I error versus time for the simulated visual system at an early development stage. In order to minimize the type I error, a Servo Position Estimator (SPE) was developed. Its math model is represented by a second order servo system with limits on the maximum acceleration. The damping factor and the natural frequency which characterize the dynamics of a second order system were varied to make the performance of the SPE close to that of the actual servo system. Figure 7 shows the result for the type I error with the SPE on. Comparing this curve to that in Figure 6, it is apparent that this estimator does help to significantly reduce the type I error.

Due to the system nonlinearity, the system, in some cases, may behave different than a second order system. Future work will concentrate on adaptive servo position estimator which will vary the estimator constants based on the system dynamic performance.

One attempt at reducing the error between the observer's gaze angle and the servo pointing angle (type II error) using CSAP was to implement a prediction scheme based upon original research by Bahill (2). Applying this concept, an algorithm was developed and implemented. The RMS of type II error was only reduced by 1% and its maximum value did not change.

A second attempt at reducing type II error was to increase the update rate of the SOPS from 60 hz to 120 hz. More specifically, updating the SOPS at the 120 hz might make it rotate at its maximal velocity with minimum delay. Due to the servo acceleration limit, 120 hz updating rate did not reduce type II error.

Reducing type II error is difficult because of the various system transport delays. However, the phenomenon often termed saccadic suppression in which the visual threshold is reduced during and after a saccade, will reduce the type II error that is perceived. The potential benefits have been evaluated using CSAP. It is also felt that the objections to type II error will probably be minimum because they are not observable until the error exceeds the AOI boundary and then results in a scene resolution change rather than object movement.

4. SUMMARY

Since the actual visual system is not available at this time, a simulation program which is called CSAP has been developed as a tool to help design the VSCDP visual system.

1. The computer simulation program that has been developed in this work has resulted in a better understanding of the behavior characteristics of the VSCDP system.

2. It has been shown that the type I and II errors can be reduced and quantitative trade-offs made by appropriately selecting the system deadband and slew rate limits.

3. A Servo Position Estimator (SPE) was developed and analyzed.

4. It has been shown that the type I error can be reduced by more than 50% using the SPE.

5. It is anticipated that during system integration and evaluation, CSAP will be used as an aid to interpreting test results and to develop further system improvements.

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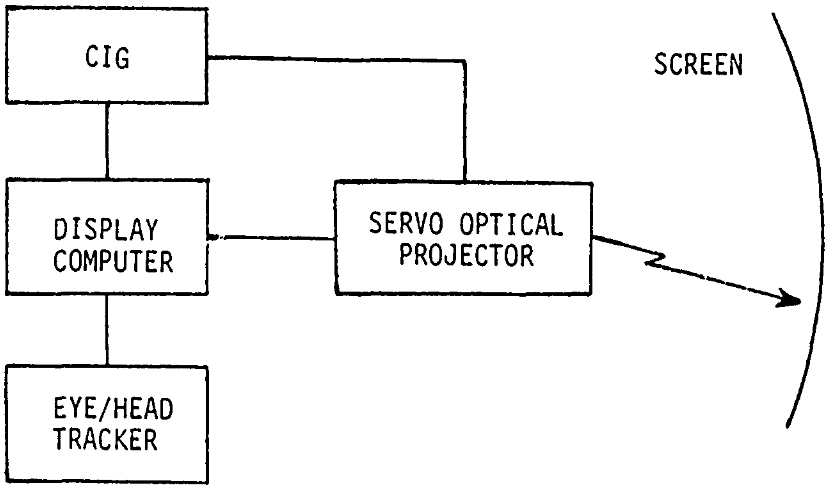

FIGURE 1. BLOCK DIAGRAM FOR THE VSCDP VISUAL SYSTEM

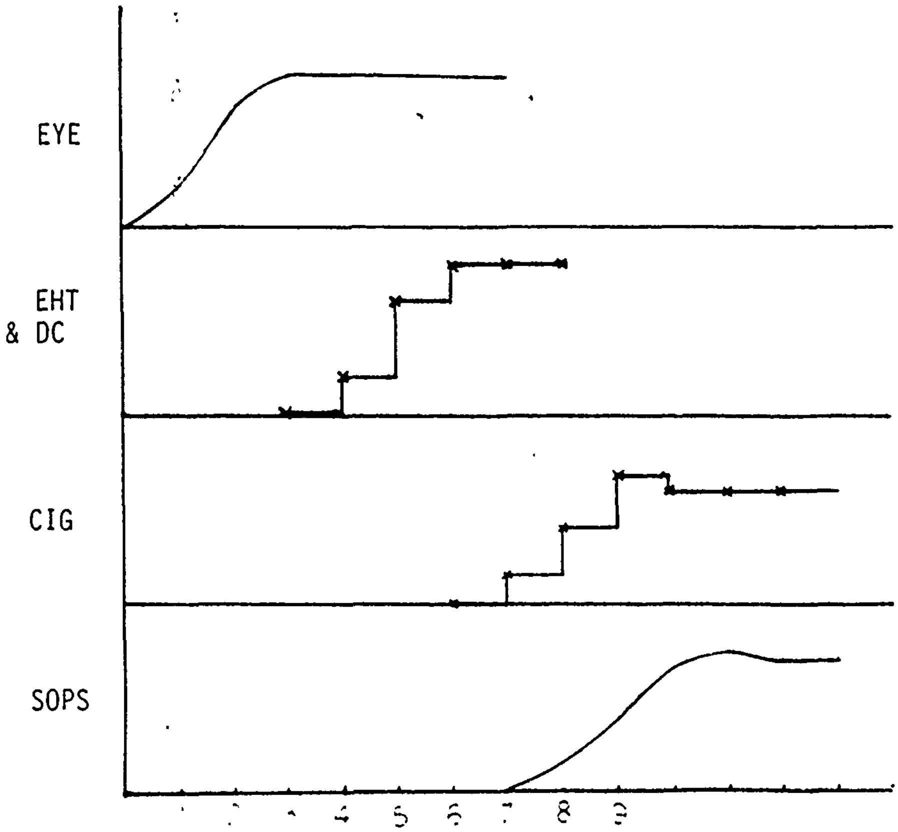

FIGURE 2. TIMING DIAGRAM FOR THE VSCDP VISUAL SYSTEM

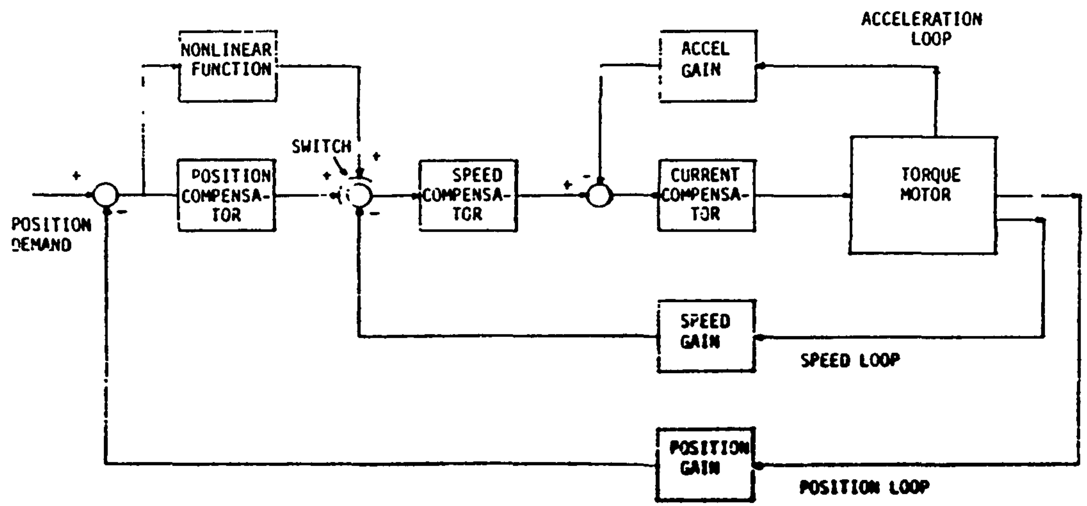

FIGURE 3. SÉRVO SYSTEM BLOCK DIAGRAM.

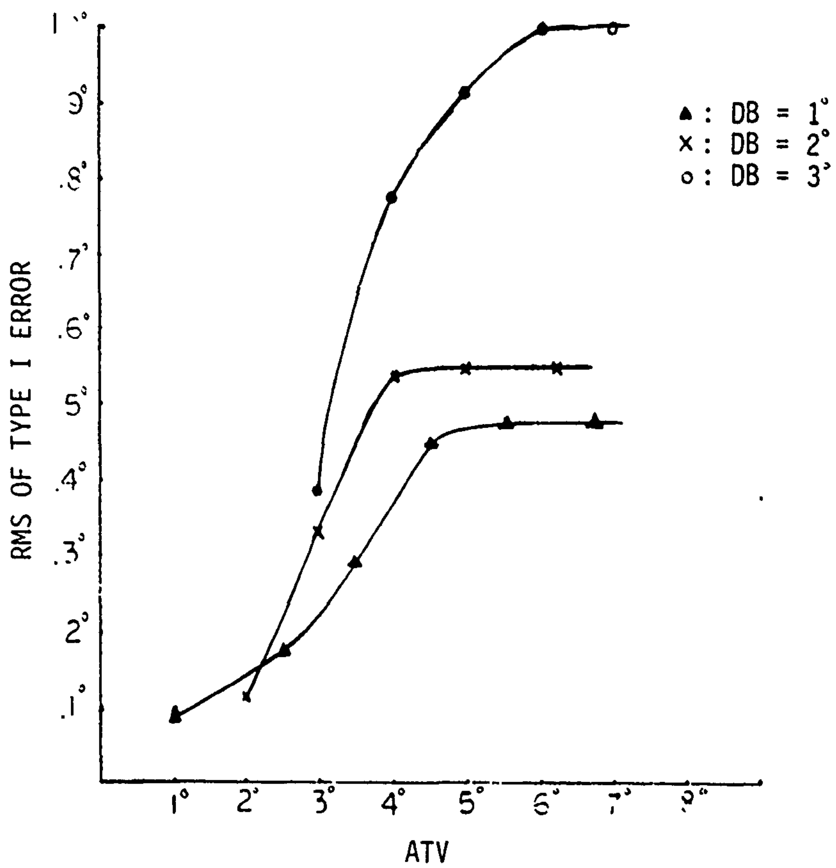

FIGURE 4(a). CURVES OF RMS OF TYPE I ERROR VS. ATV.

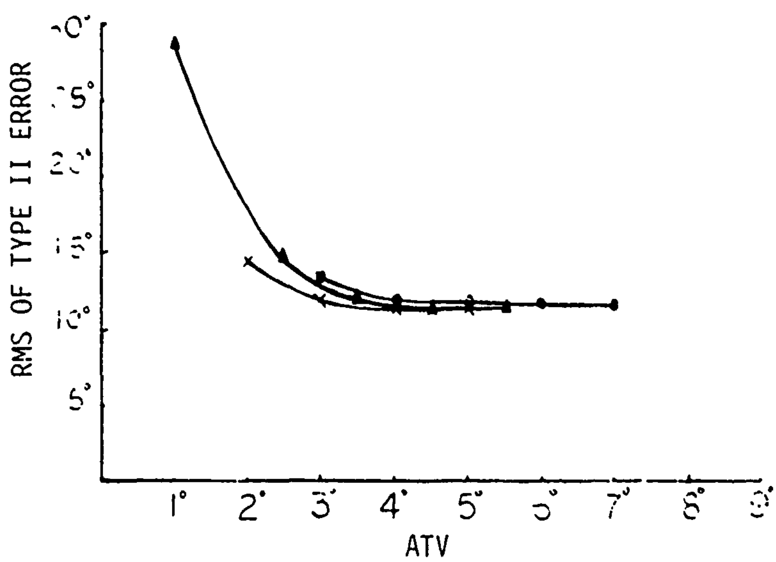

FIGURE 4(b). CURVES OF RMS OF TYPE II ERROR VS. ATV.

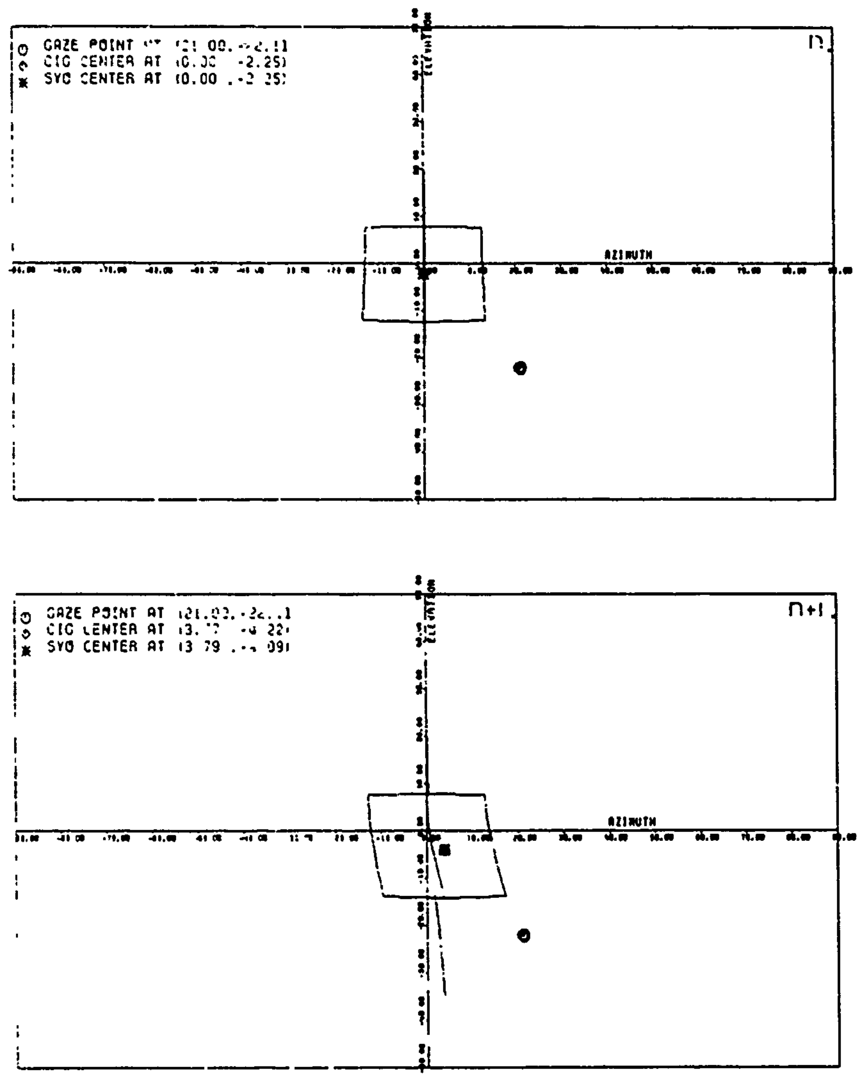

FIGURE 5 . DISTORTED AOI AND BROKEN LINE CAUSED BY SERVO MOTION.

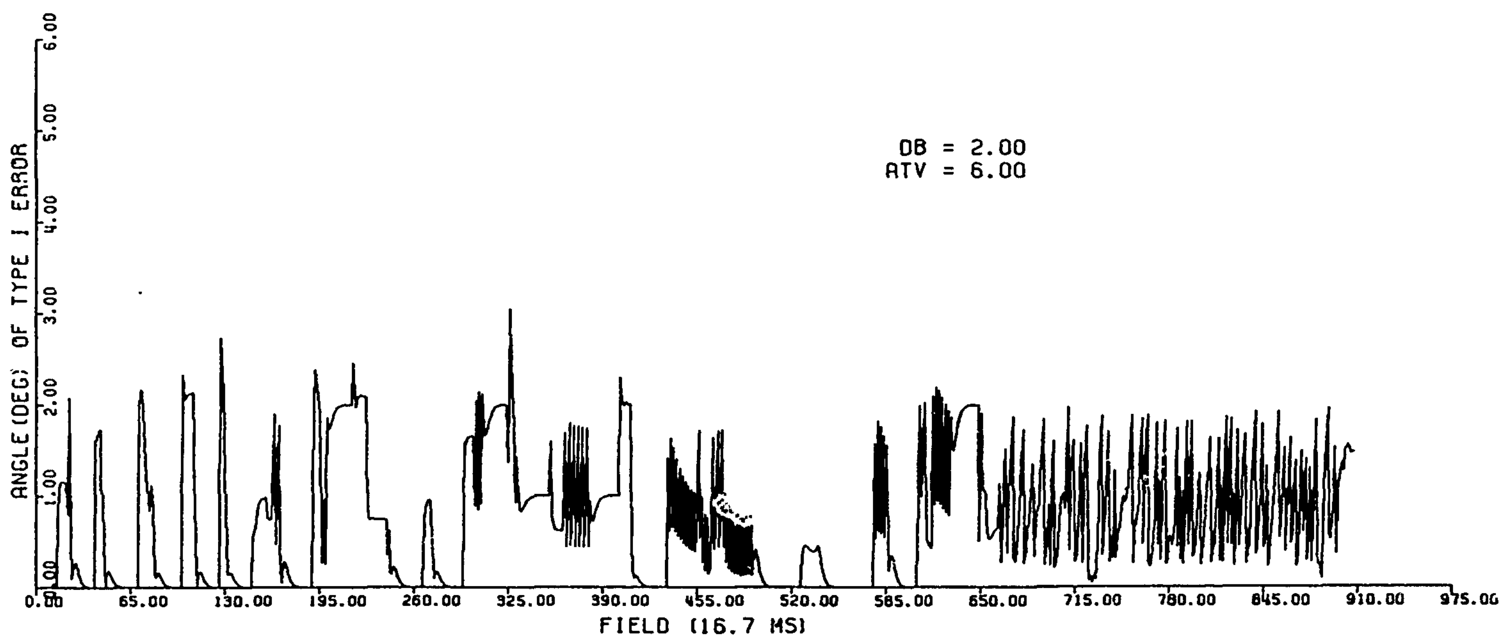

FIGURE 6. THE RESULT OF TYPE I ERROR WITHOUT USING SPE.

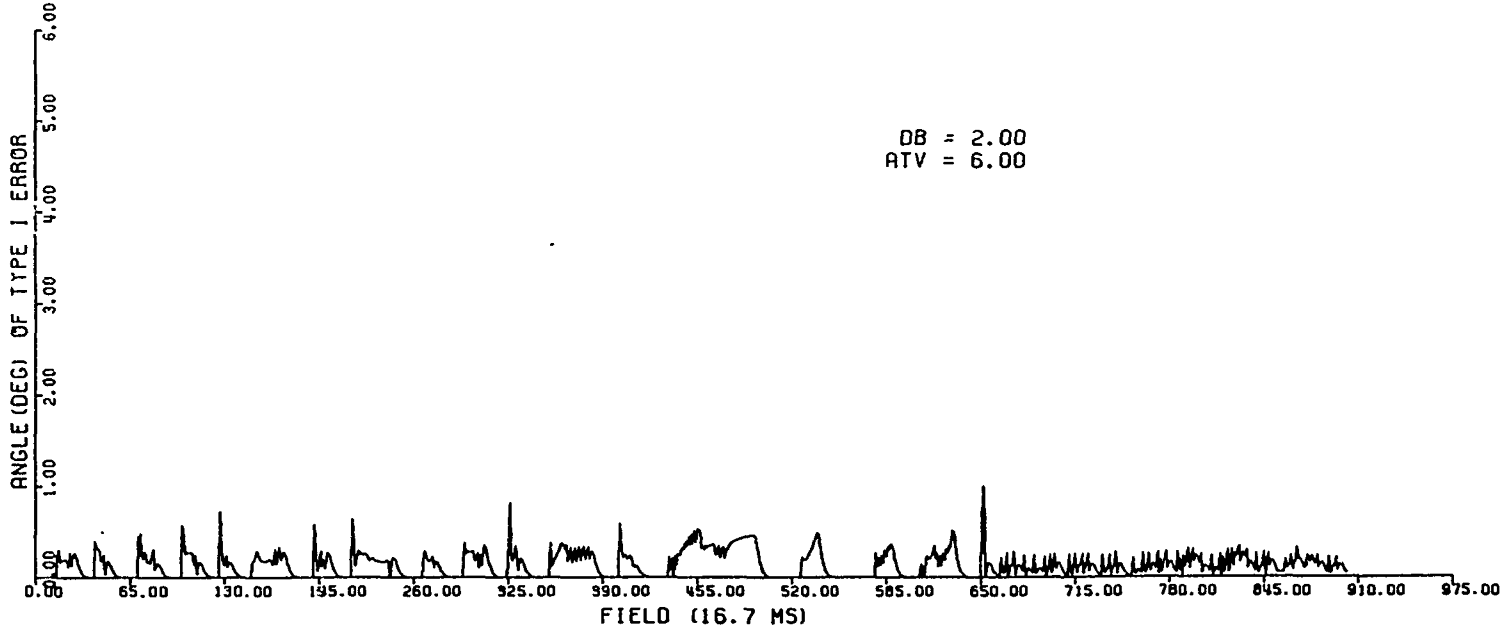

FIGURE 7. THE RESULT OF TYPE I ERROR WITH SPE ON.

PROGRESS REPORT ON AN EYE-SLAVED AREA-OF-INTEREST VISUAL DISPLAY

Hin Man Tong and Robert A. Fisher

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Robert A. Fisher is a Visual Systems Program Engineer at Link Flight Simulation Division of The Singer Company. He is currently Principal Investigator for the ESPRIT (Eye-slaved Projected Raster Inset) Visual Program and Program Engineer on the Eye-Slaved Display Integration and Test (EDIT) Program. He has over 22 years of experience in display system technology, and holds a BSEE degree from Syracuse University.

PROGRESS REPORT ON AN EYE-SLAVED AREA-OF-INTEREST VISUAL DISPLAY

ABSTRACT

A dome-projection real-image system based on an eye-slaved area-of-interest (AOI) concept has been under development for some time at the Link Flight Simulation Division of The Singer Company. The Link approach provides a high-resolution area set within a wide-field-of-view background. The display image is presented to the trainee using light valve projection on a dome screen, with the high-resolution AOI inset slaved to the trainee's eye line of sight. The display development program at Link has progressed past the system integration phase and is undergoing proof-of-concept test and evaluation. The system approach and preliminary test findings are discussed in this paper.

INTRODUCTION

The need to provide a high-detail, large-field-of-view visual training environment to the pilot-trainee, at reasonable cost, continues to pose a major challenge to flight simulation technology. Of the several candidate solutions being considered, an area-of-interest (AOI) approach to the high-resolution, wide-angle display remains the most attractive in terms of cost-effectiveness. Currently, several AOI techniques are being pursued by Government and industry. The AOI display under development at Link addresses the particular visual needs of tactical air combat flight simulators where the field-of-view (FOV) requirements are most stringent, although typically the display is to be provided only for a single observer. The Link display will offer an effective resolution of 3 minutes of arc per optical line pair (1.5 minutes per pixel) over a large FOV that is expandable to 360°. The proof-of-concept system was successfully integrated recently, and system test and evaluation is in progress.

PROGRAM BACKGROUND

The display development is being conducted under a Link IR&D program entitled "Eye-Slaved Projected Raster Inset (ESPRIT)." The ESPRIT program is an outgrowth of the engineering effort initiated under U.S. Air Force Project 2360. Although Project 2360 was terminated in 1980 due to funding problems, important results were achieved in the visual simulation area. In particular, the feasibility of an eye-slaved AOI display concept proposed by Link was studied in detail under Project 2360, and critical system components were developed which greatly reduced the technical risks of the approach. Test and evaluation of these components and the eye-slaved AOI concept have been continued under a joint Air Force and Navy program called "Eye-Slaved Display Integration and Test (EDIT)."

In 1982, encouraged by progress on various visual display component development efforts, Link consolidated the related research and development projects into the multiyear ESPRIT IR&D program. This program has led to the construction of an engineering proof-of-concept system, which is described in this paper.

ESPRIT DISPLAY CONCEPT

The ESPRIT display approach provides a high-resolution AOI area set within a wide-field-of-view background of lesser resolution, as illustrated in Figure 1. The display image is presented to the trainee by light valve projection onto a dome screen.

Separate projectors are used for the AOI (foveal) and background (peripheral) images. The background projection is fixed relative to the observer, while the AOI projection optics are servo-driven and directed by the trainee's eye line of sight. A "hole" is cut out of the background image and replaced by the AOI high-resolution inset. At the border of the AOI, the foveal and peripheral images are blended together electronically to give the appearance of a continuous picture.

On the basis of earlier psychophysical experiments conducted under Project 2360, which indicated that an eye-slaved AOI as small as 10° in diameter may be acceptable to the observer, the ESPRIT AOI is nominally set at 18°, including a 3° band for blending. Flexibility has been built into the ESPRIT design, permitting the size of the AOI and the blend region to be varied for optimization.

System Configuration

For the purpose of specifying system performance, a baseline system has been defined for the ESPRIT display. The baseline system can be expanded to enlarge the total field of view while maintaining the same system resolution by employing additional projectors. As shown in Figure 2, the ESPRIT baseline system consists of the following major components:

1) A helmet-mounted oculometer system (HMOS) that detects the observer's eye line of sight

2) A foveal projector for the AOI inset, driven by the foveal servos under HMOS command

3) Three peripheral (background) projectors for the baseline system. The number of projectors can be reduced if the FOV required is less than 270°H

4) Merge electronics that provide the blending region for the foveal and peripheral images

5) Distortion correction electronics to properly map the projected image

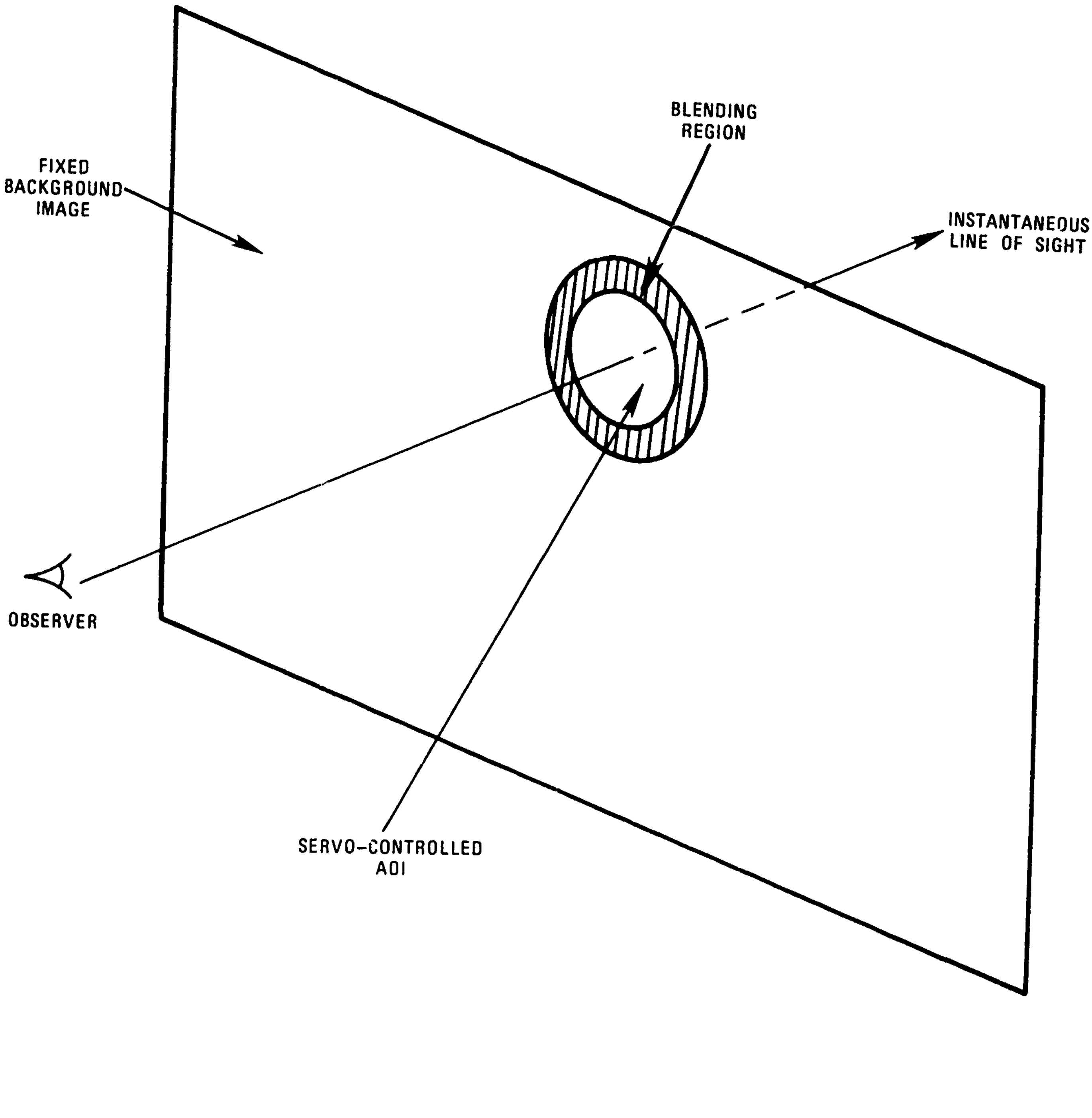

Figure 1 ESPRIT DISPLAY CONCEPT

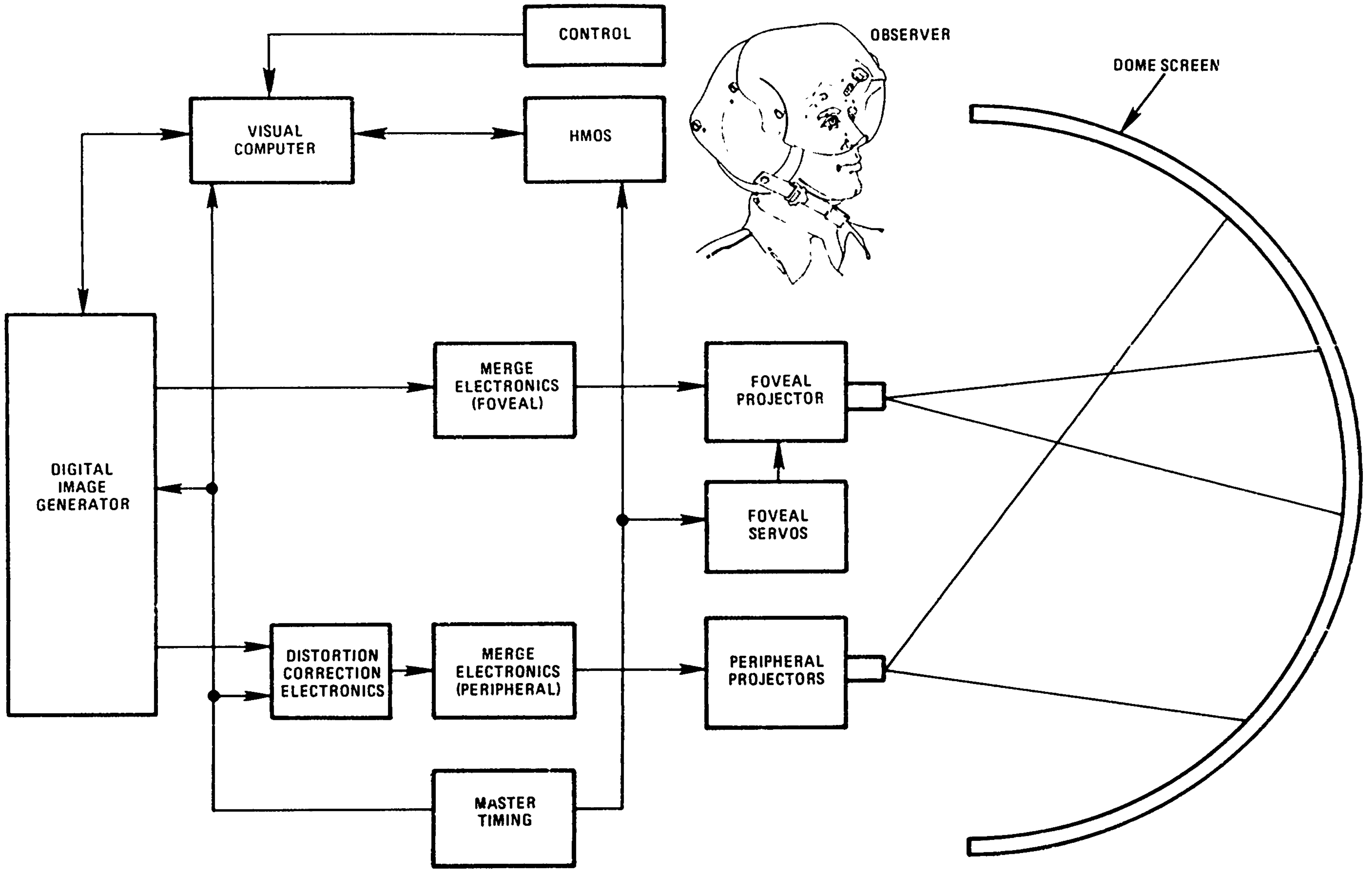

Figure 2 ESPRIT BASELINE SYSTEM BLOCK DIAGRAM

6) A high-gain, motion-compatible dome screen

The image is provided by a four-channel Digital Image Generator (DIG) fully integrated with the ESPRIT display and the host computer complex.

System Performance

The expected performance of the ESPRIT baseline system is shown in Table 1. Two items should be noted. The first is that the 270°H by 130°V FOV is limited only by the background projectors. As a result of careful design of the AOI projection system, the AOI can actually be moved to cover a larger area, as shown in Figure 3. By increasing the coverage of the background projectors, in a tradeoff against the background resolution, greater total FOV with the same high-resolution AOI can be obtained with no increase in system complexity.

The second item to be noted in Table 1 relates to head motion compensation. Most displays, real-image projection or collimated, have inherent problems in image position as a function of observer head motion. The picture presented to the trainee does not respond correctly in perspective as the trainee moves his head. This lack of parallax cues becomes more critical for objects close to the observer. The ESPRIT system design solves this problem by using the helmet positional information to shift the DIG imagery in response to the trainee head motion. The result is correct image movement so that objects located at infinity move as if they were at infinity and objects at, say, 10 feet move as if they were at 10 feet. An interesting effect will be that the observer can look "around" a small object at close range by moving his head from side to side, as in the real world.

PROGRAM STATUS

The ESPRIT proof-of-concept "brassboard" system has been assembled and successfully integrated. Initial engineering performance measurements on the system are complete. A series of psychophysical experiments will be conducted as an integral part of the proof-of-concept evaluation. These experiments are designed to address issues relating to the acceptability of the eye-slaved AOI approach. The questions to be answered range from the purely technical to those relating to visual perception and psychophysical response. For instance:

1) How well does the HMOS track the eye?

2) Critical system timing requirements were defined by early Link experimental results on saccadic suppression, using video emulation techniques. How does the proof-of-concept system perform relative to those requirements, particularly with respect to foveal servo performance and system throughput?

3) Presentation of the foveal/peripheral image does not exactly follow the visual acuity response of the human eye. What effect might that have on its acceptability to the observer?

Table 1 ESPRIT BASELINE SYSTEM PERFORMANCE GOALS

RESOLUTION	3 ARCMINUTES/OLP	FOVEAL
	22 ARCMINUTES/OLP	PERIPHERAL
FOVEAL (AOI) FOV	18° DIAMETER	
PERIPHERAL FOV	HORIZONTAL ±135°	(270° TOTAL)
	VERTICAL + 80° - 50°	(130° TOTAL)
BRIGHTNESS	5 FT-L	
DISTORTION	< 10 ARCMINUTES	
COLOR	FULL	
DOME	MOTION COMPATIBLE	
HEAD MOTION COMPENSATION	YES	

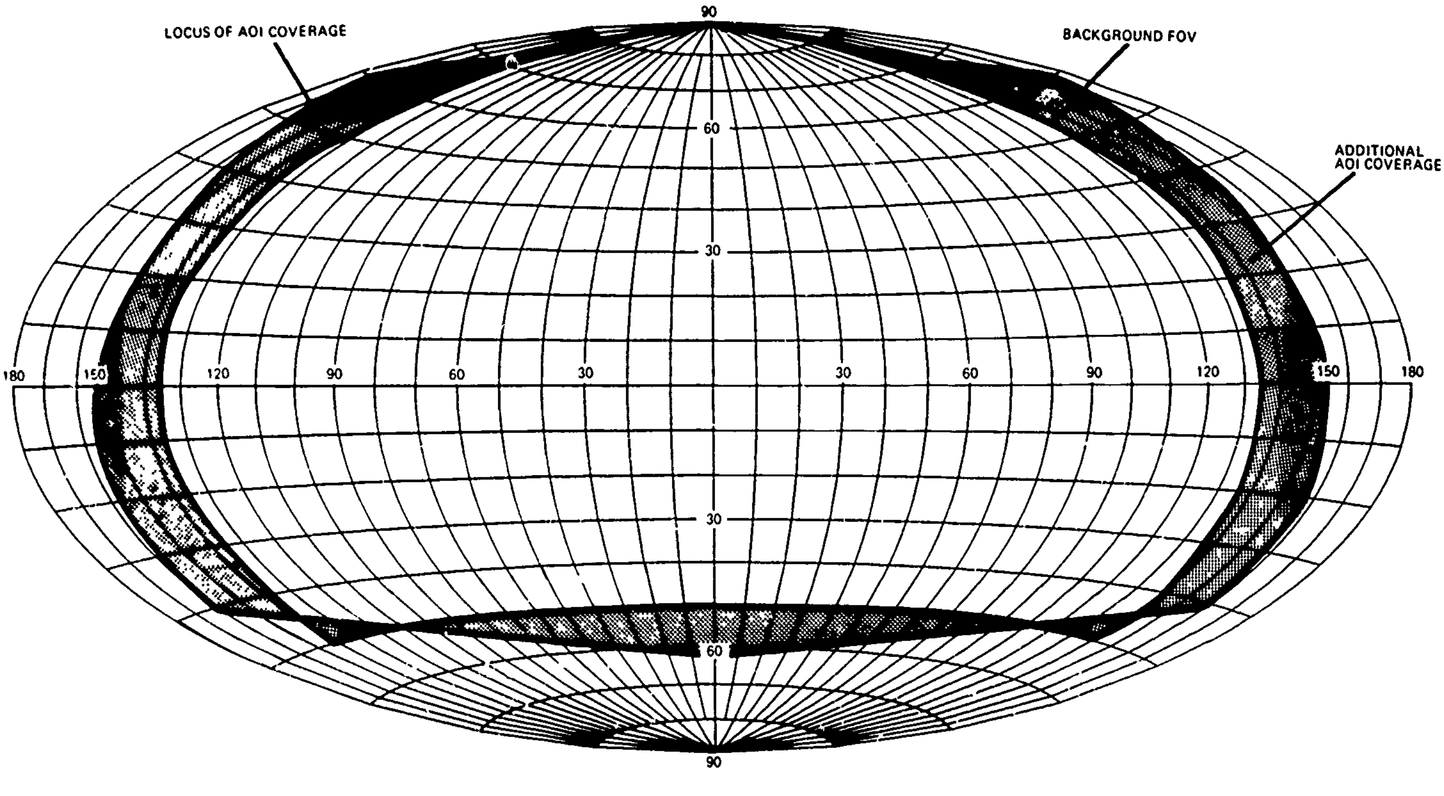

Figure 3 ESPRIT BASELINE SYSTEM FIELD OF VIEW

4) How may the AOI size and characteristics of the blending region affect that acceptability?

5) With an 18° high-resolution inset, the observer will probably be aware of the existence of the inset. Does this have an effect on his ability to perform the assigned visual tasks?

PROOF-OF-CONCEPT SYSTEM

Measurements are being taken on the ESPRIT proof-of-concept test bed to answer these and other questions. The test bed comprises nearly all the major system components shown in the baseline system block diagram (Figure 2). The difference between the proof-of-concept system and the baseline system lies primarily in the use of a flat screen as opposed to a spherical dome screen. The background FOV is reduced so that the AOI concept can be evaluated while using only a single background projector. The foveal projector is the same as in the baseline system. Distortion correction electronics, required for the final baseline system, are not needed for the test bed.

The initial evaluation of the test bed is being performed using a monochrome image. The proof-of-concept system is being upgraded to provide full color so that task performance measurements on observers can be repeated to check for any differences in results. An overview of the test bed components and performance highlights follows.

A sketch of the projection room where the observer's station is located is shown in Figure 4. It should be noted that the locations of the foveal and background projector for the test bed have been chosen for convenience. Placement of the projectors in the final ESPRIT system will be an integral part of the overall trainee station design. Figure 5 is a photograph showing the observer relative to the projection screen. A flat screen 18 feet square is used for this step of the evaluation process. The background FOV measures 74°H by 67°V, while the AOI inset is the same as the baseline system, 18° in diameter. The screen surface does not have the special high-gain finish since it is not required for the test bed. In the final design the screen will be specially prepared to provide a screen gain of up to 4, similar to the dome screen delivered to the Navy by Link and used on the Visual Technology Research Simulator in Orlando.

Helmet-Mounted Oculometer System (HMOS)

A photograph of the HMOS is shown in Figure 6. The HMOS consists of two subsystems: a helmet-mounted sight (HMS) and a helmet-mounted oculometer (HMO). The magnetically coupled HMS measures the helmet position and helmet line of sight (LOS) relative to the observer station, while the HMO measures the observer's eye LOS relative to the helmet. The HMS and HMO measurements are then combined to obtain the eye LOS with respect to the observer station. The resultant eye LOS and helmet position information is used to control the position of the foveal image.

The HMOS uses a charge coupled device (CCD) camera to view the pilot's eye, which is illuminated by a low-intensity, near-IR light source. The CCD picks up the illuminator's reflection from the observer's cornea along with his pupil image. Using this information, the HMOS system computes the observer's eye LOS with respect to the helmet.

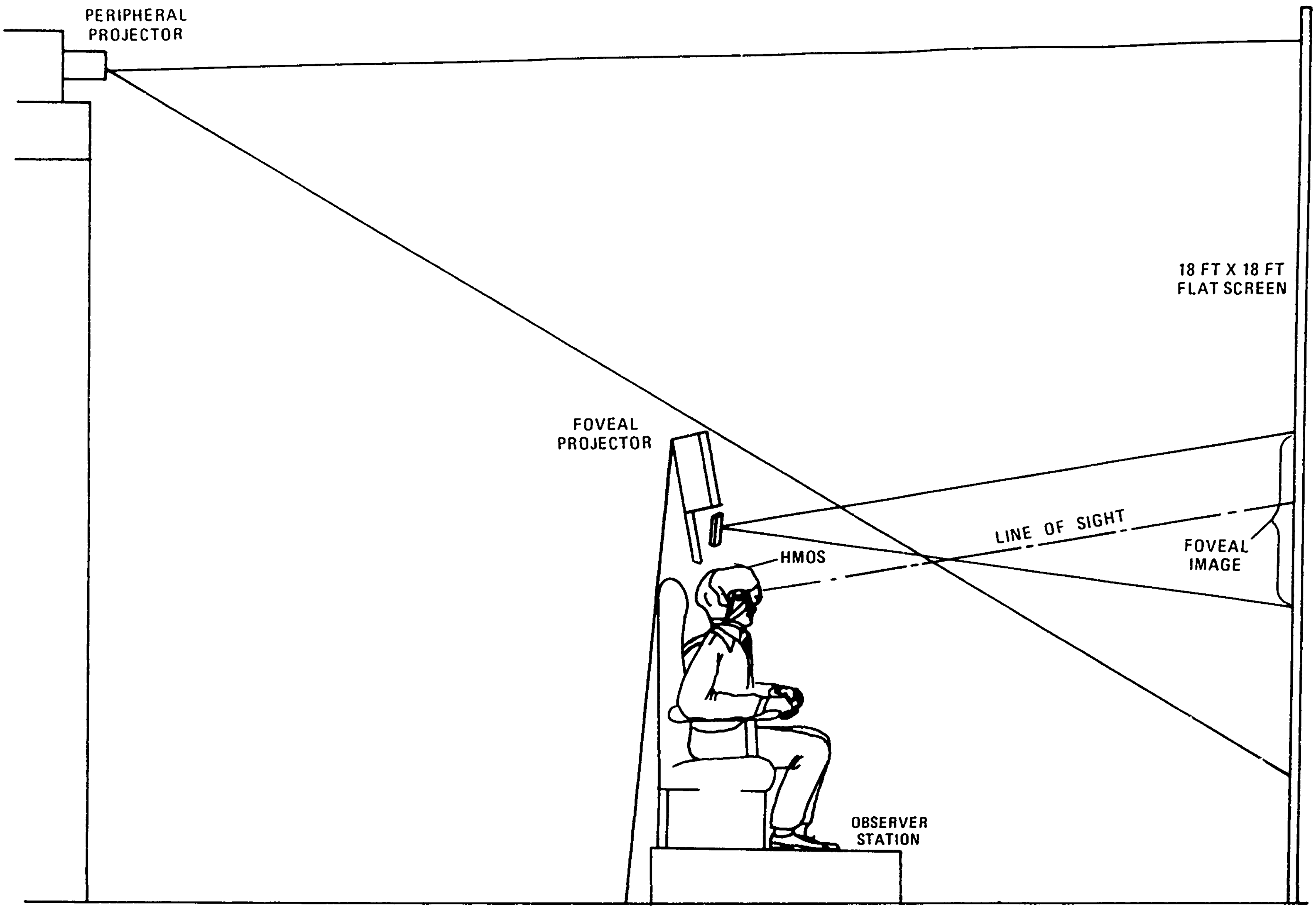

Figure 4 PROJECTION ROOM ARRANGEMENT

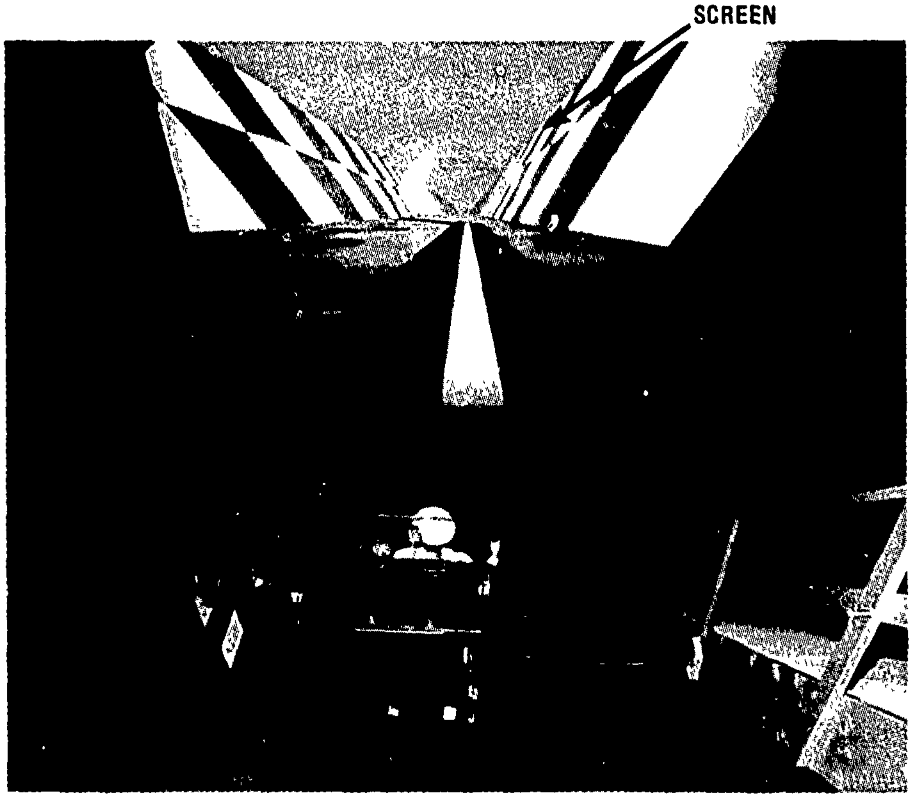

Figure 5 PHOTOGRAPH OF OBSERVER AND SCREEN

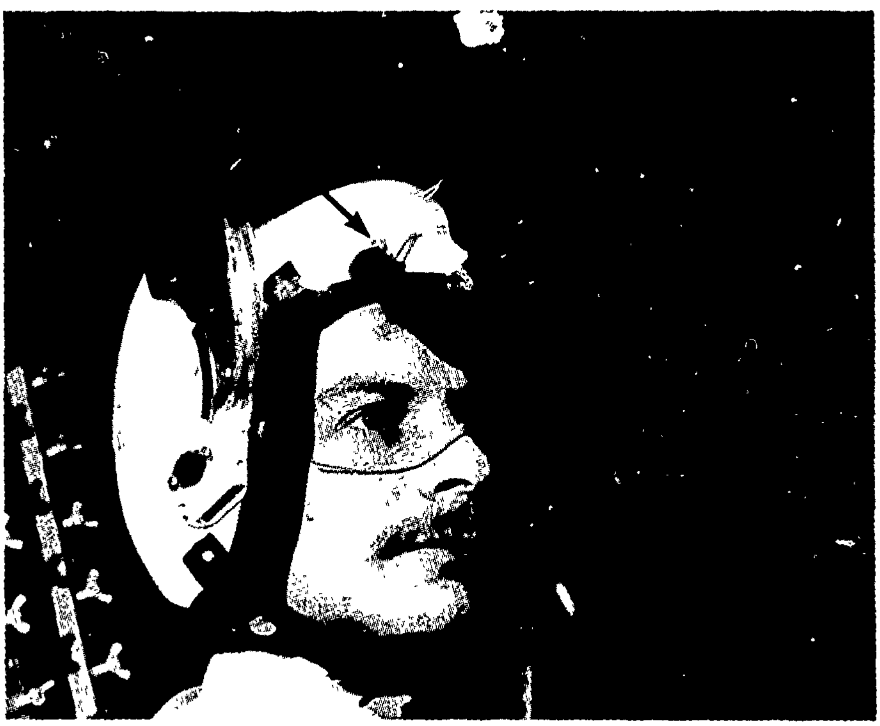

Figure 6 HELMET-MOUNTED OCULOMETER SYSTEM

The accuracy and repeatability of the HMOS exceed the requirements originally specified under Project 2360. The integrated HMOS/foveal projector is able to consistently place the foveal image where the observer is looking. The positional accuracy of the DIG picture in the central region of the screen is better than 6 minutes of arc. The picture is composed of the AOI high-resolution zone and the background portion. Placement of the high-resolution zone is to within 3 degrees of the actual eye LOS. What this means is that, given the HMOS accuracy, the observer LOS will always be within the AOI area. He cannot look directly at the blending region or go past it into the peripheral area.

Foveal Projection Assembly

The foveal projection assembly for the AOI inset image is shown in Figure 7. In addition to the light valve projector display image source, the assembly contains all the optics and servos needed to project the AOI image. The azimuth/elevation servos (shown in closeup in Figure 8) drive the output projection mirror as directed by the observer's eye LOS. (Derotation of the image, required for proper orientation as the azimuth servo turns, is provided in the digital image generator.) Three other servos are used to maintain constant image size, focus, and brightness as the LOS changes and the foveal projection throw distance varies.

The azimuth/elevation servo design is among the most difficult engineering tasks accomplished for the test bed. Angular velocities of up to 200°/s are required when the eye is in the tracking mode. Eye saccade step responses can demand velocities that exceed 700°/s and accelerations of up to 50,000°/s^2.

These velocity and acceleration requirements, as well as smooth operation at minimum speed, are all met by the brassboard hardware. The static LOS accuracy of the azimuth/elevation servos is better than 1 minute of arc. The dynamic accuracy is better than 3 minutes at an angular velocity of 700°/s. Errors in AOI placement caused by the servos are thus negligible.

The five servo subsystems use the same design, that of a single microprocessor-based digital position loop controller. This commonality has been achieved although the servo requirements differ greatly. Some are continuous servos, others noncontinuous, with different requirements in velocity, acceleration, and output resolution. In addition to superior performance and modular design, the foveal servos are highly maintainable. An adaptive, self-calibration capability has been built into the servo system, operating off-line.

The AOI size on the test bed, as mentioned earlier, is set at an 18° diameter. At this FOV the measured display resolution is better than 3 arcminutes per optical line pair.

Peripheral Projector Assembly

The peripheral projector assembly in the test bed is located above and behind the observer (see Figure 4). A light valve equipped with a wide-angle lens provides the full screen coverage. The background image resolution is

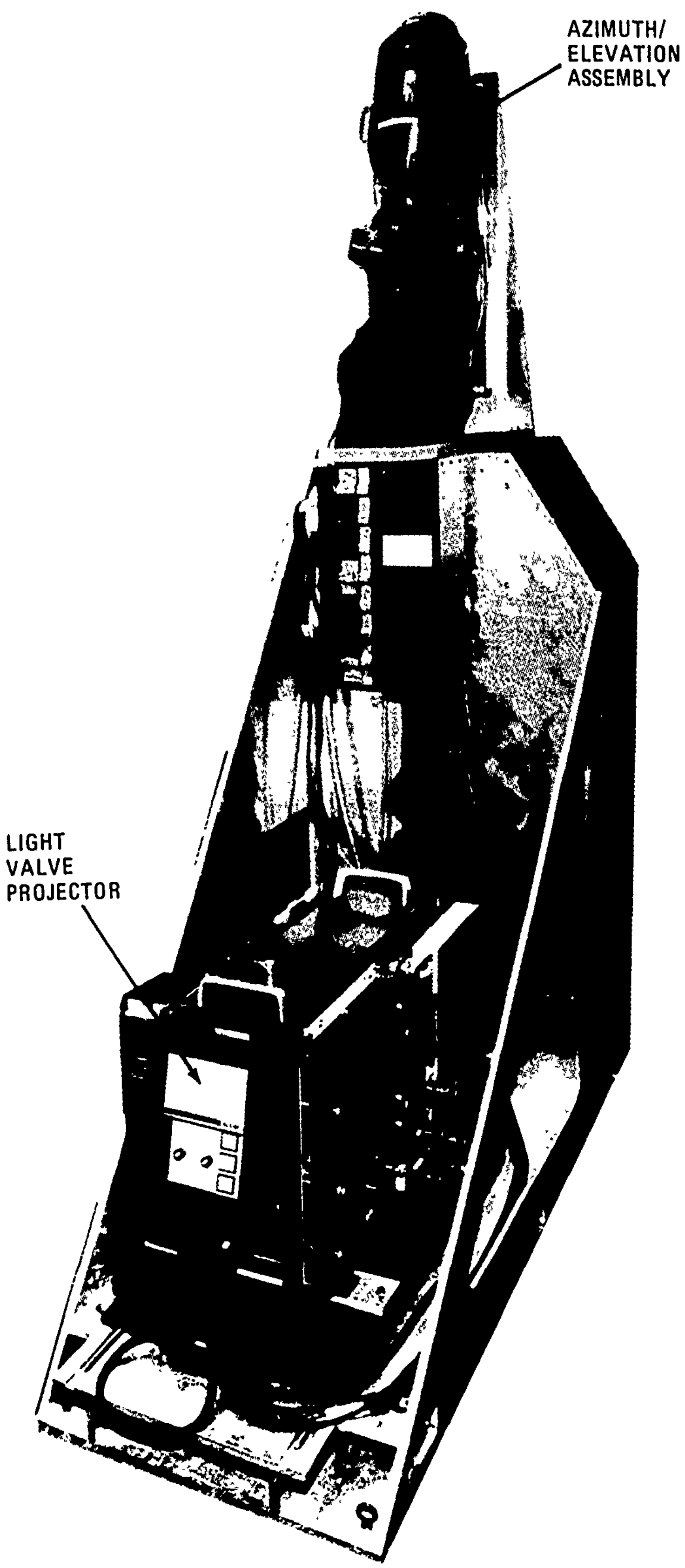

Figure 7 FOVEAL IMAGE PROJECTOR

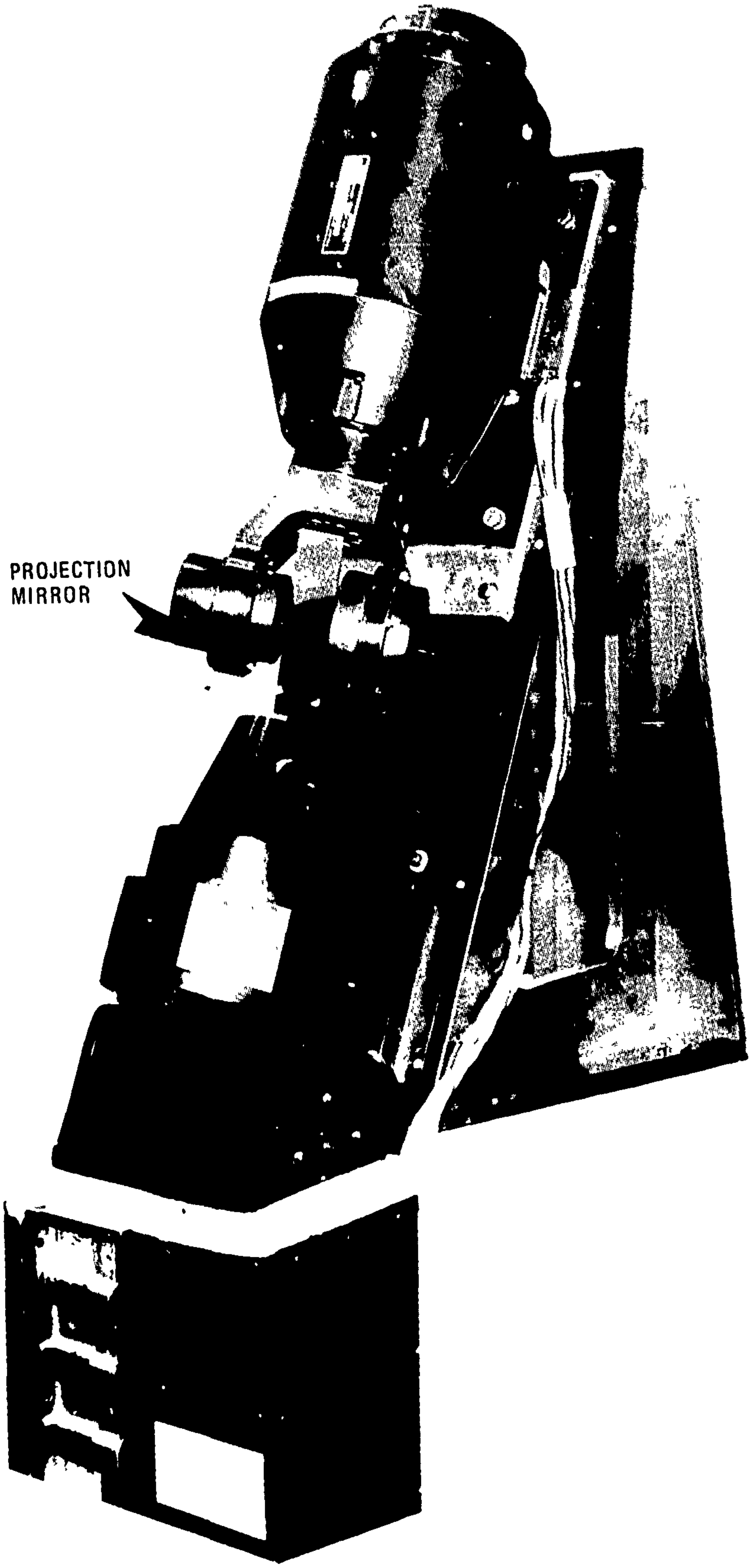

Figure 8 CLOSEUP OF AZIMUTH/ELEVATION SERVO ASSEMBLY

approximately 11 arcminutes per optical line pair, with a peak-white brightness measured at 5 foot-lamberts. A contrast ratio of better than 15:1 is obtained.

Merge Electronics

The merge electronics provides the proper blending of the foveal image with the peripheral. An elliptical hole is cut out of the peripheral image by blanking the video drive signal for the peripheral projector. The edge of the hole is feathered to blend with the foveal inset. Positioning of the peripheral hole is controlled by the observer LOS. The size of the hole and width of the feather functions are under software control.

The foveal image is similarly shaped by the merge electronics and projected into the peripheral hole. The combined picture gives the appearance of a continuous image.

Tests results so far are encouraging. As discussed above, the HMOS provides precision eye-tracking so that the observer's LOS is always within the foveal image high-resolution inset under normal operating conditions. Consequently, the observer can never look directly at the blending region. It has been reported that with an AOI size of 18°, the observer is generally aware of the existence of a high-resolution AOI that is different from the background; however, it was also found that the distinction between foveal and peripheral images tends to be forgotten once the observer is task-loaded.

Host Visual Computer Complex, Master Timing Electronics, and Miscellaneous Items

Additional hardware items make up the balance of the proof-of-concept test bed. There is a host visual computer complex as well as master timing electronics to synchronize the throughput of the system. Video test patterns are built into the test bed electronics to aid routine maintenance.

A summary of the ESPRIT proof-of-concept system performance is given in Table 2.

Psychophysics Experiments

Informal, subjective evaluation of the ESPRIT test bed from a human factors standpoint has been proceeding for some time. Link is about to begin a series of formal, human-in-the-loop measurements to obtain some quantitative behavioral results. Psychophysical experiments will be conducted to assess the perceptual acceptability of the Link AOI approach. Subjective response to the picture, particularly to the high-resolution inset, will be evaluated. Effect of the AOI size and characteristics of the blending region on the observer will be recorded. Attempts will be made to quantify the ability of the test subjects to perform tasks that require a high-resolution picture over a large FOV while using the AOI display.

Table 2 PROOF-OF-CONCEPT SYSTEM PERFORMANCE SPECIFICATION

FOV	74^{o}H x 67^{o}V
RESOLUTION	3 ARCMINUTES/OLP FOVEAL 11 ARCMINUTES/OLP PERIPHERAL
BRIGHTNESS	5 FT-L
CONTRAST	15:1
COLOR	MONOCHROME
HEAD MOTION COMPENSATION	YES

Test data bases for the DIG have been prepared in accordance with the experimental design. Initially, a group of people who are technically oriented and knowledgeable in visual flight simulation will participate as observers. The reason for the initial special sample is to provide feedback so that technical imperfections reported can be corrected on the test bed as rapidly as possible. The enhanced test bed will then be used for a broader sample of the general population in formal experiments.

CONCLUSION

While behavioral aspects of the ESPRIT system have yet to be fully evaluated, the technical feasibility of the Link display approach has clearly been demonstrated. The objective of an eye-slaved AOI display is to give the observer-trainee the perception of a high-resolution image anywhere within the FOV. If the performance of the ESPRIT test bed is an indication, the effect of a display with 1.5 arcminute/pixel resolution, covering a field of view of 270° to 360°, can be breathtaking.

As the psychophysics experiments progress on the test bed, Link will continue working on system improvements. Development of additional components needed for the baseline system is proceeding, including the distortion correction electronics design. Other engineering tasks, such as construction of the dome and refining the high-gain screen finishing process, will be added.

As the ESPRIT display development gets closer to completion, work on the image generation process to take advantage of the eye-slaved display will be pursued; i.e., concentration of scene detail in the AOI. The rapidly advancing technology of computer-based image generation coupled with the ESPRIT display will permit a level of performance never before achieved in visual flight simulation.

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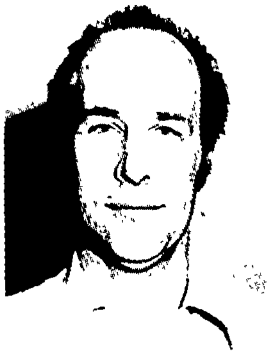
AIR COMBAT VISUAL SIMULATION USING A HEAD SLAVED PROJECTOR



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Malcolm E Roberts has worked mainly at Rediffusion Simulation Ltd since 1960 with a break from 1970 to 1976. During this seven year period he worked as a Research Fellow in Electronics and Educational Technology at Chelsea College, University of London, where he obtained M.Phil and Ph.D research degrees. He is also a Charterd Engineer and a Member of the Institution of Electrical Engineers and the Institution of Radio and Electronic Engineers.

Owen Wynn received his BSc in Physics from Sussex University in 1975. Since then he has worked as a Development Engineer at Rediffusion Simulation Ltd.

AIR COMBAT VISUAL SIMULATION USING A HEAD-SLAVED PROJECTOR

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Abstract

An experimental system is described which is aimed at providing a low cost air combat training capability by the use of a head coupled projector giving a wide angle display with a high resolution central region and a low resolution peripheral region.

Introduction

Rediffusion Simulation Limited started investigating area of interest (AOI) displays in the days when imagery was derived from modelboards using CCTV. The initial work resulted, in 1974, in a design[1] for a helmet mounted projector having a 32° by 24° instantaneous field of view centred on the pilot's head pointing direction. Freedom to move the head was achieved by having a projector, fixed in the cockpit behind the pilot, projecting an image down a jointed optical relay assembly which allowed motion in the yaw pitch and roll axes and which was fitted with angle sensors to provide head orientation angle information to drive the optical probe at the modelboard.

The introduction of computer generated imagery removed the limitation of a single channel limited field of view display imposed by the television camera/probe assembly and opened up the opportunities to explore more exotic approaches providing much larger fields of view. The provision of wide fields of view of uniform high resolution imagery is expensive and may not be necessary if the resolution of the image is tailored to match that of the eye, but this can require eye tracking to keep the high resolution imagery centred on the fovea.

The Company had gained experience of using lasers to produce high resolution wide angle colour imagery[2] and used this knowledge to develop the concept of a helmet mounted projector[3] in which the lasers and polygon line scanner were mounted on the cockpit structure behind the pilot and the line scan was relayed to the pilot's helmet via a fibre optic link, with a projection lens and

frame scanner mounted on the pilot's helmet. This design was developed further and reported to NAVTRAEQUIPCEN[4] where it was used to derive the Visual Display Research Tool (VDRT) concept[5].

The design reported to NAVTRAEQUIPCEN[4] would have been expensive to implement, had a degree of risk involved, and required extensive modifications to the computer image generation system to which it would be coupled. An alternative approach was sought which would allow demonstration of the area of interest concept whilst using as much "standard" hardware as possible to reduce the risk, cost and timescale.

Design Concept

Rediffusion had developed a three tube calligraphic projector[6], with excellent raster shaping control for distortion correction when projecting on to a spherical screen, which gave a 30° by 40° field of view and was compatible with the Novoview[7] range of image generators.

Evans and Sutherland Computer Corporation had developed the Digistar lens, an f2.8 colour corrected lens projecting a 160° cone angle from a 5 inch crt. Mounting the Digistar lens on one tube of a calligraphic projector, with a second tube giving a 30° by 40° field of view would give a wide angle picture in which the central region was high resolution (centre of interest or COI) and the peripheral region was low resolution[8] (wide field of view or WFOV), as shown in figure 1.

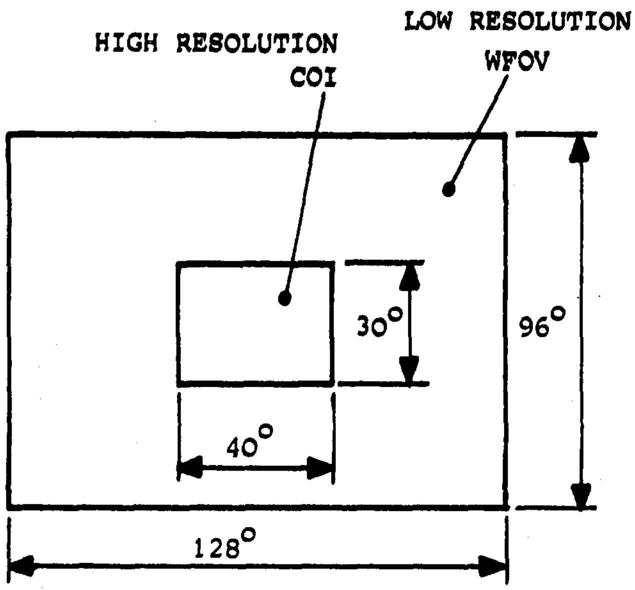

Figure 1

If such a projector is mounted so that the centre of the image, both COI and WFOV, tracks the pilots point of gaze then the resulting picture will appear to be a wide angle high resolution image.

A survey of the literature on head and eye movements[4] showed that most eye movements relative to the skull are less than 15°, with peaks of 30°, and that the dynamics of the head and eye tracking systems appear to be well matched and to have a bandwidth of the

order of 2 Hz for reasonable amplitudes of movement. The magnitude of eye angular rotation increases with head rotation, with 90% of fixations occuring at angles of less than 10° eccentricity, and 96% within 20° eccentricity. Thus, for a 40° wide COI image, we can expect 96% of all fixations, including intense visual search, to fall within the high resolution area when the centre of this area is steered by skull angles.

The relationship between head and eye rotations has been measured[7] and is shown in figure 2. From this data the measured head rotation can be used to assess the point of gaze and the centre of the display positioned at this point.

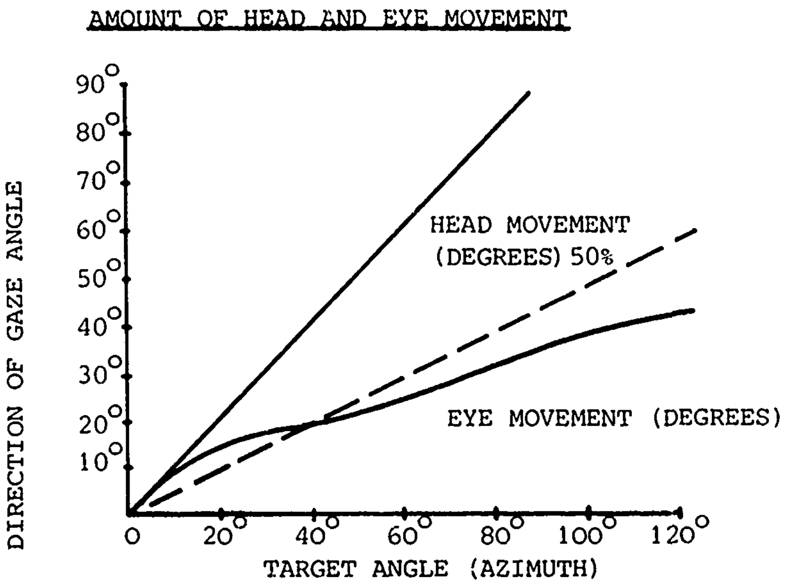

Figure 2 (after T C D Whiteside[7])

Thus, if the projector is mounted on a gimbal to give yaw and pitch rotations with a 2 Hz bandwidth, and driven to the computed gaze point, the image will appear to be high resolution and wide angle. The coupling between the pilot's head and the projector can be fairly loose, but tight coupling between the projector and CIG system is required to ensure image stability.

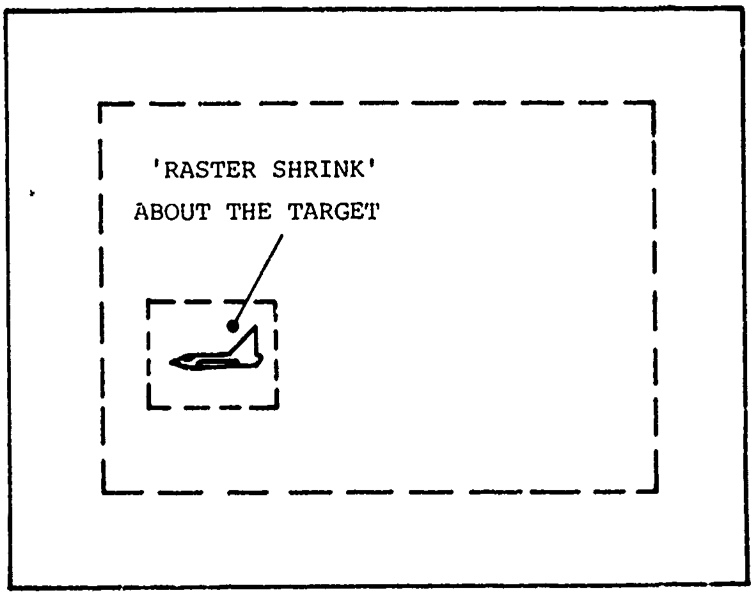

Figure 3

If the COI and WFOV images are superimposed, with the terrain always being shown in the wide angle display, then the high resolution projector will only display a target aircraft, and hence raster shrink may be employed to give an enhanced long range image. Raster shrink, however, must be applied about the target centroid, as shown in figure 3, which, in general, will not be aligned with the optical axis of the projector. Should the target eccen-

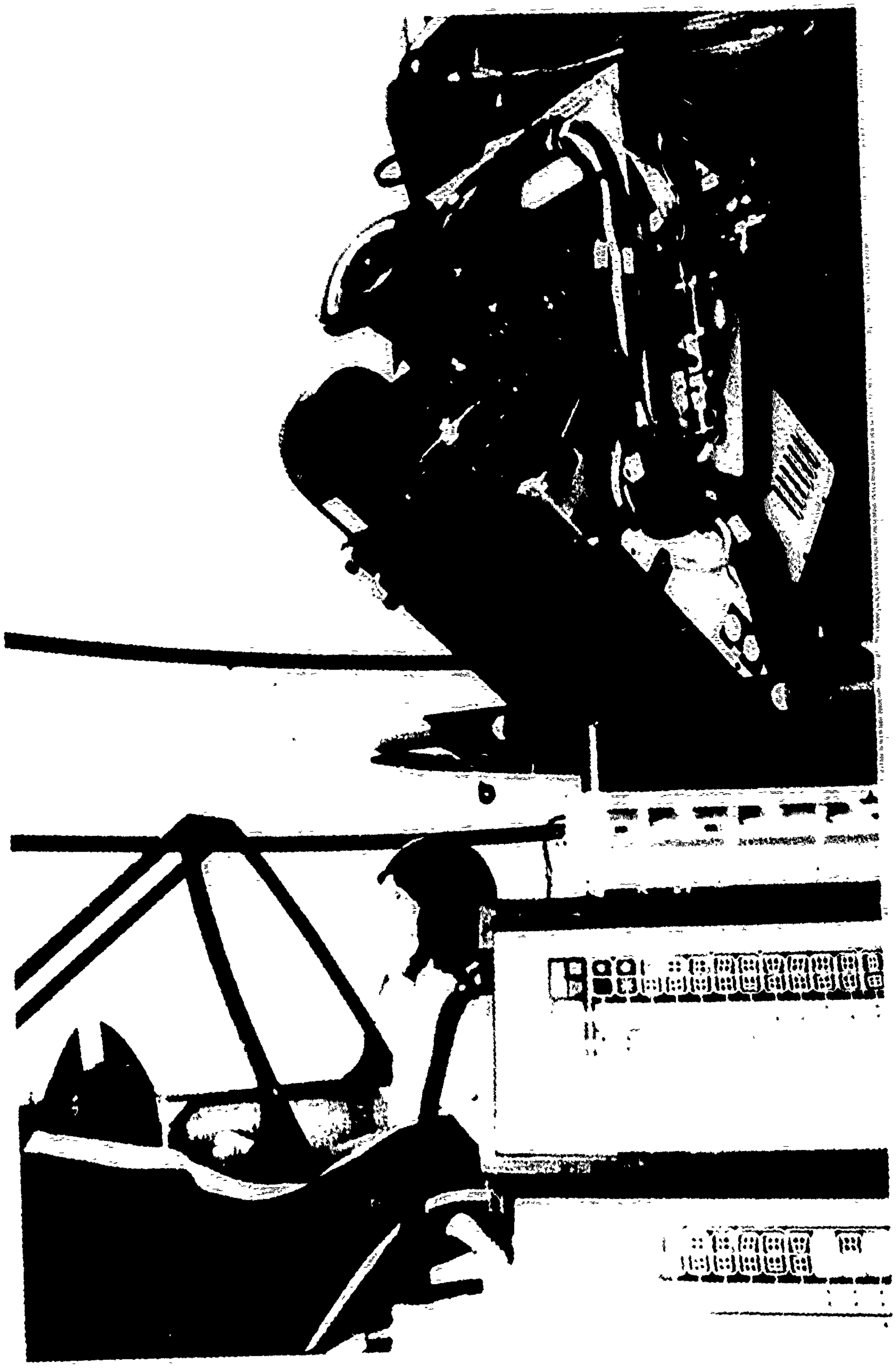

Figure 4

tricity grow large enough then it is displayed in the low resolution peripheral image.

The system outlined above will give a reasonable match with the resolution capability of the eye with increasing eccentricity, and it will enable a pilot to engage in visual search to locate the target. Furthermore, if a second narrow angle tube is used in the third position on the projector then two independent targets can be portrayed each with its own independent raster shrink control.

System Description

The design concept outlined above has been built into a small dome with a simple cockpit and flying controls and a separate target control station to allow an assessment to be made of the effectiveness of the approach.

Display System

The projector is hung in a cradle so that it can be rotated in the Euler sequence yaw and pitch with the axes intersecting at the centre of the screen. This cradle assembly is illustrated in figure 4. In this way, irrespective of projector orientation, the viewing distance and projection geometry remain unaltered. Because the projector occupies the central position in the sphere the pilot is located below and in front of the screen centre. There are, however, distortion problems for an observer viewing the display off axis, discussed in more detail below.

It is desirable, therefore, that the vertical separation is minimised and that the screen radius be as large as possible. However, through using existing hardware an unsatisfactory situation was reached because the screen diameter was small (16 feet) and the projector was large and bulky, in consequence the horizon dip was 15°.

Projector movement limited by its relatively large size, was for +/- 57° in yaw and +/-30° in pitch. It was decided in using these figures that the motion available would be sufficient to investigate the head slaved AOI concept even if full mission performance were not possible. Having set limits for the movements in the two axes it was possible to design hydraulic systems to drive the projector. The yaw actuation system used two jacks in pull-pull mode with the drive being conveyed by a pair of cables. The pitch motion was produced by a single jack of the same type as used in the yaw axis, operating on an eccentric pin basis.

Projection System

In order to produce the two displays necessary for an AOI demonstration, it was decided to modify a Rediffusion Calligraphic Projector. The three standard Red, Green and Blue Schmidt projection tubes were removed and the two top mounting locations used for the Wide Field of View (WFOV)/Centre of Interest (COI) projection tubes and lenses, and the third mounting location was used for an additional fan cooled deflection amplifier. The modified projector is shown in Figure 5. Because only one tube is used for the projection of each channel the display is monochrome, initially white (P45 phosphor) but was changed to whitish green (P53 phosphor) mainly to achieve higher screen brightness. The two projection systems are significantly different and are discussed separately.

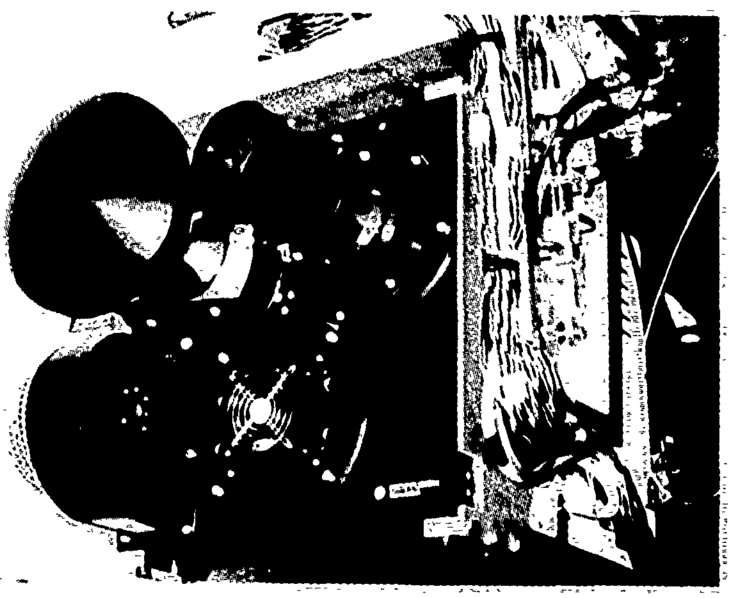

Figure 5

WFOV Projection Sytem

The Evans and Sutherland 160° cone angle F2.8 Digistar projection lens was used as the output element which for a 4" x 3" raster on a 5" diameter flat face Cathode Ray Tube gives a 128° x 96° display in the dome. This large angular coverage produces a low brightness unless the brightness of the image on the CRT faceplate is high. To achieve the necessary brightness the tube is driven with a 50 KV EHT supply capable of supplying 2mA, leading to a significant heating effect, which is minimised by forced air cooling across the faceplate. The drive conditions can produce a faceplate raster brightness approaching 65,000 candelas per square metre when used with a P53 phosphor.

COI Projection System

This system has a standard 30° x 40° projection format. The Cathode Ray Tube was similar to that in the WFOV system (ie: 5" flat face with P53 phosphor). The emphasis, however, for the performance of the COI tube differs from the WFOV unit; in that very high brightness requirements are replaced by the need for high resolution (small spot sizes). This high resolution is

required so that targets can be portrayed with good definition at long range[9], giving realistic air combat cues. The lens used was a US Precision plastic type using aspheric perspex elements. The performance of this lens was generally good, but does provide some problems by not being colour corrected. The chromatic abberation totally precludes the use of a white phosphor and even provides marginal problems with P53 green phosphor since the P53 phosphor light output profile shows some red and blue emission. The overall COI performance was acceptable.

Distortion Correction

Three main types of display distortion are present on the COI system, these are:-

1 Tangent Mapping Correction

The wide angle lens maps in spherical co-ordinates: this means that equal translational increments on the faceplate are projected as equal angular increments in image space. The Novoview[7] range of image generators, however, computes the picture information in equal increments on a viewing plane. Therefore, an unmodified CGI signal projected on a spherical screen from the wide angle lens would exhibit very large amounts of pincushion distortion. This distortion is corrected by modifying the CGI deflection signals inside the projector with a $\tan^{-1}$ correction algorithm derived from a purpose built analogue multiplier system.

2 Off-Axis Viewing Distortion

This error is caused by the pilot viewing the display from below the projection point. This error is explained more fully later (see equation 1).

3 Residual Distortions

Small distortions are inevitable on this type of display with causes such as non-linearities in scan amplifiers, optics, coils and minor errors left from the more complex $\tan^{-1}$ correction system and these all need to be removed. The importance of having a near perfect geometry set up can be seen by considering a pilot in a stationary aircraft rotating his head (and, therefore, the projector) and attempting to view a stationary object. This object would remain 'nailed' to the screen if distortion were not present. However, any geometry errors would cause a lack of image stability or picture swimming, an effect which had to be minimised. In order to achieve the optimum picture set up condition both the WFOV and the COI were designed with flexible control electronics allowing the manipulation of 26 separate correction terms. The control boxes can be seen in figure 4.

VISOR (Visual Intensity, Shrink and Offset)

This is a purpose designed piece of electronics designed to manipulate the COI picture with commands from a Z8001 micro-processor. It performs three functions:-

1 Shrink

The microprocessor informs VISOR as to the amount of shrink required. The circuitry then accurately reduces the drives to the scan amplifiers to maintain the scan line density across the target[19].

2 Offset

Analogue multipliers are used to move this shrunken image around the faceplate so that the target image is always located in the correct position relative to the observer, as shown in figure 3.

3 Intensity Variation

When a raster is reduced in size a constant electron beam energy excites an ever decreasing area of phosphor. This energy density increase leads to a higher elemental brightness. The applied compensation law aims to maintain the same picture brightness over the total shrink range.

Computing

The system cpu was a 16 bit Zilog Z8001 micro-processor supported by a high speed multiplier to effect a considerable reduction in computation times. All system software was written in assembler code for speed of execution and iterated at 160 Hz maximum rate with half and quarter rates for less critical algorithms.

The software was responsible for the servo control, projector and CIG look angles and shrink factors, flight equations and on-line monitoring facilities.

The flight equations used a reduced set of aerodynamic derivatives and contained no ground handling since air combat was the primary objective.

The hydraulic servo systems for yaw and pitch were digitally controlled, states being measured by high resolution optical encoders, velocity transducers and load cells. The pitch servo is illustrated in figure 6. System performance in terms of damping and linearity was controlled by pressure and velocity feedback respectively owing to the third order nature of hydraulics. Feedforward compensation was provided by software

filters to produce a combined system bandwidth greater than the 2 Hz necessary for successful head following.

The pilot head angles relative to the cockpit were measured, using a simple mechanical head tracker, filtered and used to drive the projector such that the WFOV channel was aligned to the gaze angle. This was a fairly casual coupling with low absolute accuracy but excellent phase response. The projector angle, known to 15 bit accuracy, was then used to derive the CIG look angle to provide correct spatial image location. Transport lags within the CIG pipeline would normally cause such images to be unstable under head motion so projector velocity and acceleration were used to produce extrapolated angles negating this effect. This was an adaptive facility tracking the CIG lags which varied according to data-base and image content. Intra field image swim due to projector motion during the image painting period was removed by applying a voltage equal and opposite to the integral of the angular velocity of that axis as measured by the servo velocity transducer. Since the CIG could not be synchronised to an external source, nor the microprocessor to it, the asynchronous software for this critical area was run at 160 Hz to ensure that the CIG received data no older than 6.25 mS. All these precautions ensured excellent image stability under all but extreme head movements.

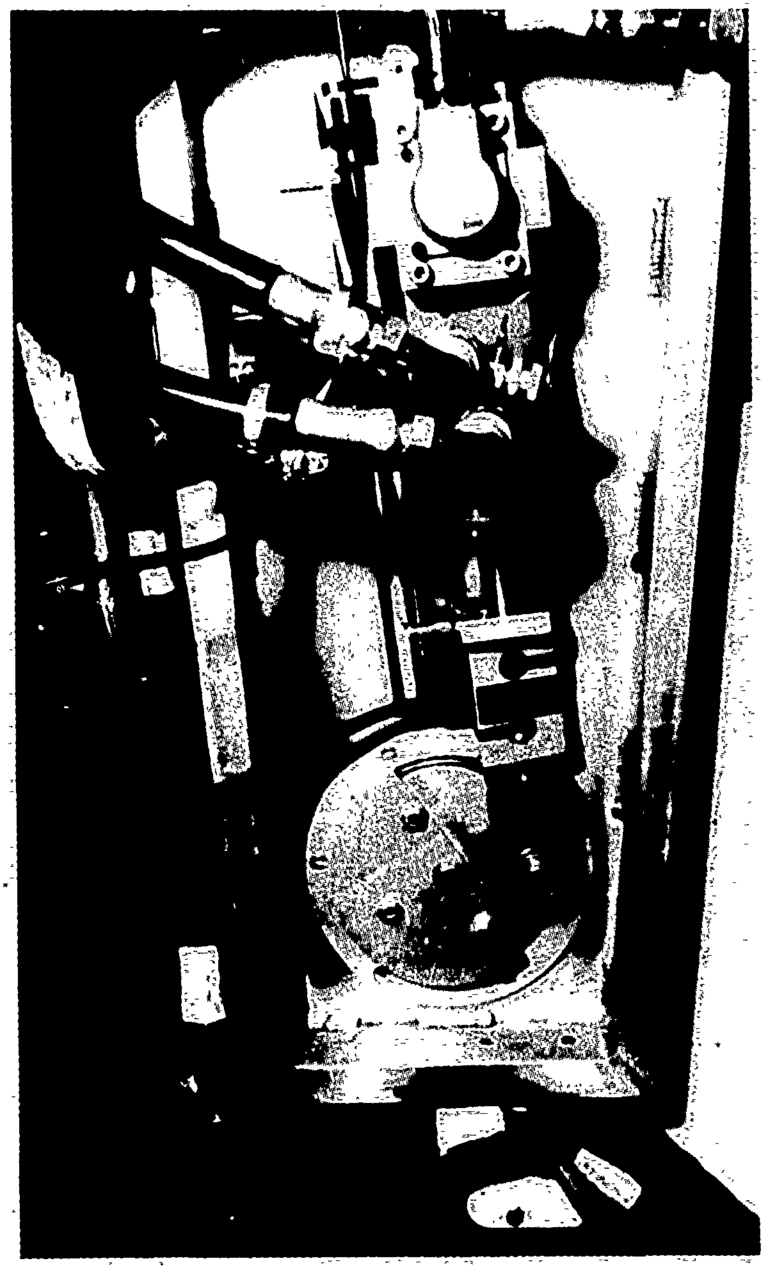

Figure 6

The ideal look angle for the LOI channel is at the relative yaw and pitch of the target aircraft image whilst the ideal image

shrink factor is such as to maintain the target in a box just larger than itself. Practical constraints limited the shrink ratio to 4:1 and the orientation to be $\pm 15°$ at maximum shrink.

Software computed these limited values and transmitted the data to the CIG in the form of target image orientation and half angle corresponding to the image shrink factor. Finally offsets were computed to place the COI channel target image at the same point in space as the WFOV channel. Electronics in the projection system converted the offsets into x and y deflection voltages and the shrink factor into a size control.

Pipeline buffers were present in VISOR to ensure that changes affecting both CIG and projection system occurred in the same visual field and were therefore indiscernable.

Computer Generated Imagery (CGI)

The CGI system available for the project was the SP2 image generator[4]. This is capable of providing full colour but since the displays were monochrome this colour capability was not used. The lights in the model displayed by the SP2 system are "painted" calligraphically whilst the surfaces are painted using a raster scan which is rotated so that the raster lines are always parallel to the horizon. The output video is corrected within the CGI system for the display gamma while display geometrical distortions are corrected in the display system itself.

One CGI channel is used for the centre of interest display and a second channel for the wide angle display. As described earlier both channels are coupled to the projector orientation, and hence to the pilot's head position but with the axis of the centre of interest channel biased towards the position of the airborne target within 15° of the wide angle display axis. Thus each channel has a central axis which can be dynamically changed relative to the aircraft axis and which can be dynamically changed with respect to each other. In addition the centre of interest channel has a field-of-view which is controlled dynamically in accordance with the angular size of the target; this computes the raster shrink effects in order to maintain display resolution for distant targets. The CGI software was suitably modified to incorporate the dynamic changing of these parameters.

The model of the target aircraft consists of about 200 surfaces and typically 100 or so surfaces will be visible at any one time. Low detail ground is also modelled: this was displayed only in the wide angle channel. The target aircraft is a dynamic target which is visible on both the centre of interest display and the wide angle display when the pilot looks in the right direction. Thus the target could first be detected in the pilots peripheral vision and as the pilot turns his head to acquire the target, it will move into the centre of interest channel. At this stage, in the present system, the target is painted twice, once in the wide

angle display and then in the centre of interest display; it follows that the target is brighter under these conditions.

This identifies one of the major problems of any area of interest display viz. the maintenance of reasonable relative brightness between the area of interest display and the remainder of the display. Obviously the target will get brighter as it crosses the centre of interest display boundary. This is further emphasied by the shrinking raster tending to increase the target brightness as the angular size of the target decreases, ie: as the target goes further away; this is compensated for in the display drive to some extent by reducing the centre of interest video level as the raster shrinks. Although the required brightness relationship is not a simple one this compensation worked adequately in the air to air combat mode.

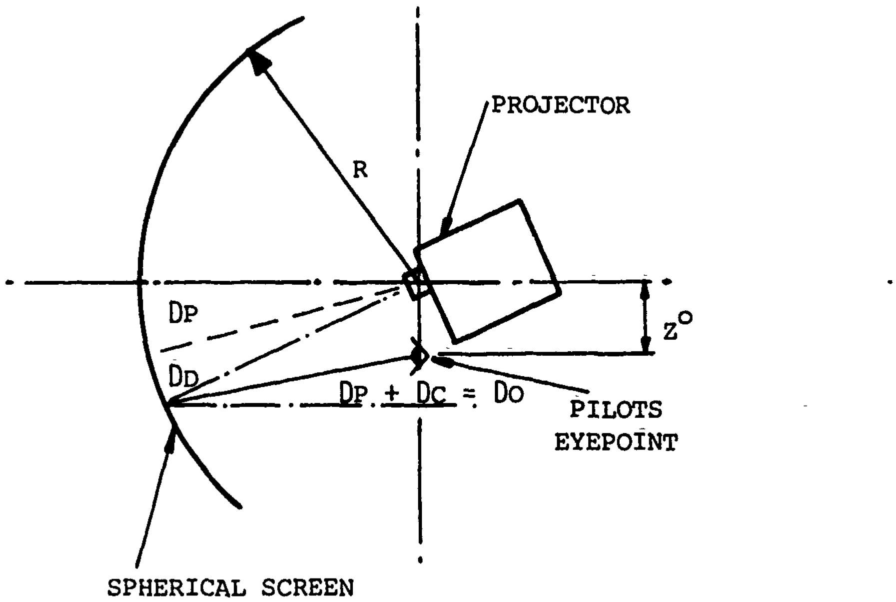

Figure 7

A second problem concerns the distortion due to the viewing system viz the pilot's view point is not at the centre of the spherical viewing screen. Assuming the pilot sits directly below the centre of the sphere (which is the effective pivot point of the projector) there is vertical distortion in the image when viewed from the pilots position (see figure 7). This distortion which is discussed later cannot the corrected within the SP2 system and must be included in the display system.

A third potential problem concerning the CGI was the variation in the computation and display time with reference to the CGI update time. In fact this transport delay was not noticed once the servomechanism angle compensation was working.

Demonstration Capability

It was considered that in order to evaluate the potential of the CDI concept, the pilot observing the display would have to be put into as near a realistic environment as possible in order that he may judge the value of the display whilst performing real tasks. This posed three problems:-

1 Host Aircraft

The pilot sitting in the dome must have sufficient equipment and cues to allow him to fly the visual successfully. To do this it was considered sufficient to provide a wooden cockpit with stick, rudders, throttle and four illuminated instruments, (speed, thrust, angle of attack and height above ground). All these instruments were operational and were driven from the central microprocessor.

2 Flight Dynamics

It was considered that full flight dynamics were not required for this application. Aspects such as ground handling, air brakes, supersonic performance and all minor terms were ommitted; however, enough terms were entered to give the impression that the aircraft being flown could have been a single engined jet fighter such as a British Aerospace Hawk. (The target aircraft had the same flight equations but was given greater thrust to give the host pilot a sterner task).

3 Target Aircraft Control

To provide an aircraft for the host pilot to 'chase' it was considered that the most cost effective approach was to have a separate pilot with a comprehensive Head Down Display, figure 8, which gave information about both aircraft. It was felt that if this pilot had sufficient information he could manoeuvre so as to provide the host pilot with a reasonable task.

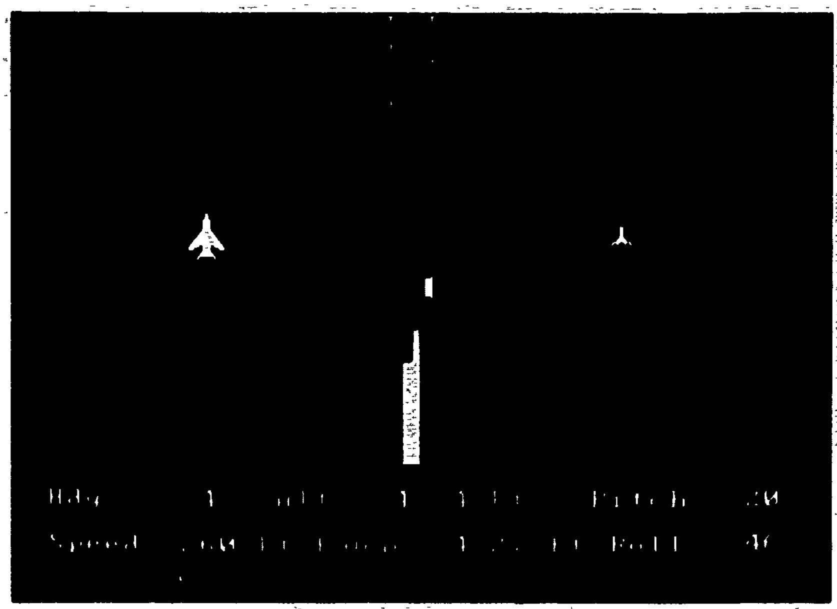

Figure 8

Performance

The visual system has been operational for three periods corresponding to milestones in the Ministry of Defence contract. This contract at the time of writing is not yet complete and thus further technical work has yet to be done prior to a final assessment. Several milestones have already been achieved, these are:-

1 Image Stability

The image on the screen has been shown to be stable for all reasonable head movements (erratic head movements cause picture disruption but this error stabilises prior to the human visual system being conscious of such disruption). This stability is achieved through having the micro-processor, projector hydraulics, CGI and shrink and offset systems operating in synchronism. It also implies that display geometry is well corrected. (The error due to the off axis viewing (artificially high horizon) cannot be readily corrected without introducing some image instability.

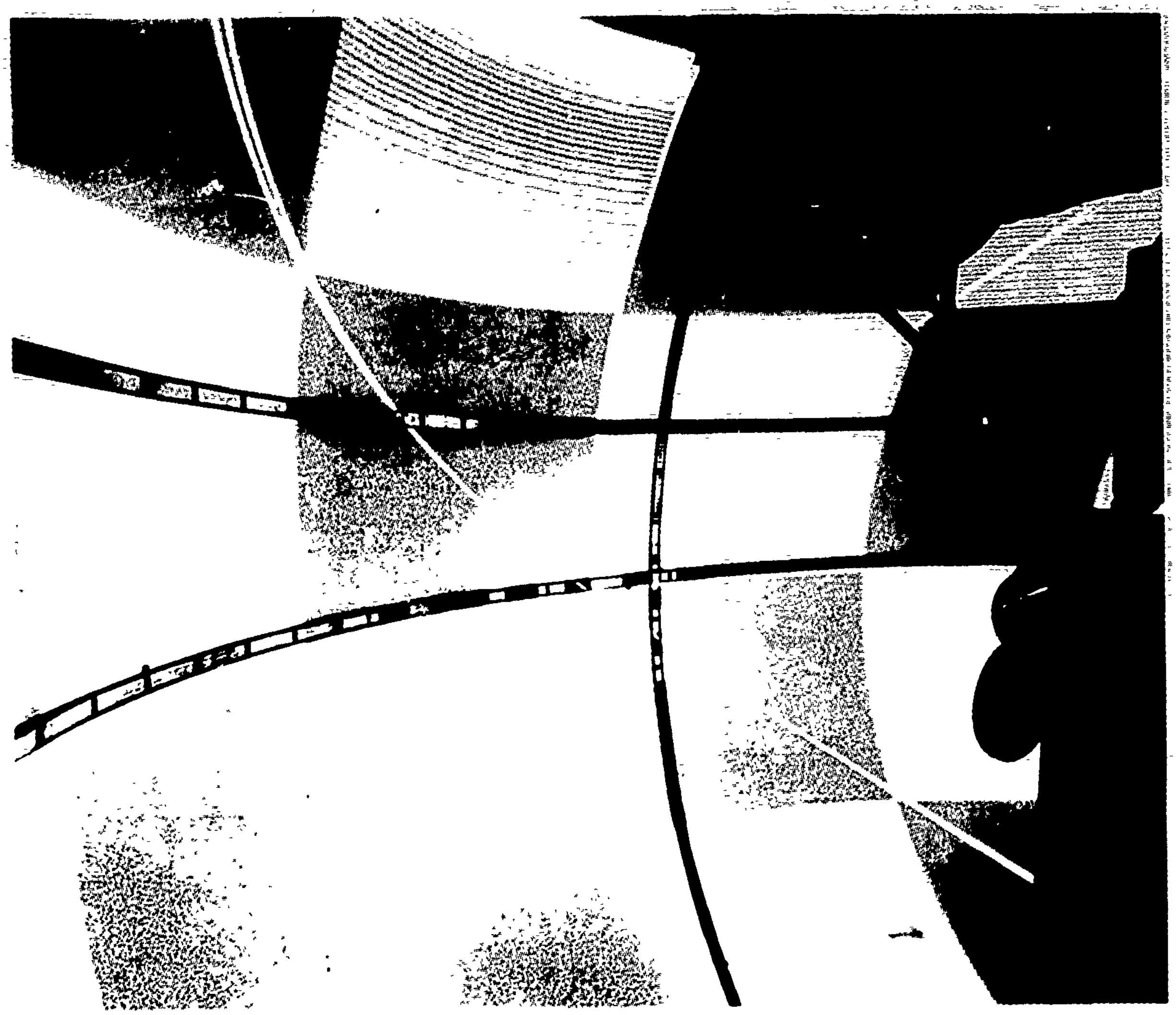

Figure 2

2 Field of View and Brightness

Full fields of view ie: 128° x 96° WFOV and 30° x 40° (shrinking to 7.5° x 10°) COI have been achieved. The wide angle display achieved a brightness of 0.6 candelas per square metre raster brightness. This brightness has been adjudged to be easily sufficient for assessment purposes. The aircraft target when in the WFOV has a brightness level well above the 0.6 cd/m^2 due to the use of calligraphic light points and is thus easily visible to the observer when in his peripheral vision zone. The COI has a brightness capability (if required) in excess of 6 cd/m^2. The relative display brightness and relative resolution are illustrated in figure 9 which shows the COI (the fine chequer board pattern) superimposed on the WFOV (the coarse chequer board pattern).

3 Resolution

In order to be able to conduct realistic air combat manoeuvres it is essential that the pilot is able to discern the attitude of the target aircraft at realistic distances. This requires a good resolution capability on the COI display. The measured separation of the aircraft at which the attitude and direction of the target are clearly visible is over 8000 feet. However, the target remains visible in the diplay to over 20,000 feet. Combat pilots from the RAF and USAF commented that visibility in real air combat rarely exceeded the achieved figures.

4 Hydraulic System Performance

The hydraulic system has given a smooth and reliable movement mechanism, and has never been considered insufficient for the task. The measured performance can be summarised thus:-

Yaw	Amplitude - +/-57°
	Response - 2Hz at 1/6 radian peak to peak
	Velocity peak - 1 radian/sec
	Acceleration peak - 13 radian/sec^2
Pitch	Amplitude - +/-30°
	Other data same as for Yaw

5 General Impressions

Whilst the research hardware is not complete several current fighter pilots from the RAF and USAF have flown the host aircraft. Their general impressions have been unanimously favourable, with none of them unable to fly the visual. In fact with only the COI visual to provide attitude and target position cues they all were able to fly complex combat

manoeuvres without losing contact with the independantly flown target which, as previously noted, had a thrust advantage.

Future Development

More detail is required for the model of the airborne target to enable the pilot to detect and recognise the direction of flight at longer ranges and to anticipate rapid changes in energy. The SP2 system is capable of providing more general detail and to simulate control surfaces and afterburner effects; some further modelling is required in this area.

Turning now to ground targets, the problems discussed earlier become more difficult to solve. The matching of the brightness of the centre of interest display to that of the wide angle display is now more critical since there will nearly always be ground features straddling the boundary between the two displays which will emphasise discrepancies in brightness. This is further complicated by the gammas of the two crts; even when the gammas are matched, the two crt's will be working at different beam currents and therefore on different parts of the gamma curve. Further, the relative brightness of objects (and the continuous perspective of the ground plane) in the attack area form part of the pattern of cues for estimating target range and lack of fidelity in this area will generate misleading range cues as well as detracting from the realism of the scene.

In the ground attack case therefore it will probably be necessary for the centre of interest to be inserted in the wide angle scene where the wide angle video has been blanked so that the centre of interest imagery is only painted once. The gamma corrections should then be done individually for each crt to enable good brightness tracking between the displays.

The problem of image distortion is also an area which requires development work. In theory the display would be accurate if viewed from the centre of the sphere. Assuming the pilot sits directly below this point there is vertical image distortion from his view point. The distortion is described by the following general equation:-

$$(1 - a) \tan (D_P + D_D) = \tan (D_P + D_G) + af (D_P + D_G, A) \ldots \text{ eq 1}$$

Where D_P is the depression angle of the projector (see figure 7); D_D is the desired depression angle of the crt deflection; D_G is the depression angle defined by the CGI output deflection signals which assumes the pilot is at the centre of the sphere; a is the ratio of the vertical displacement of the pilots viewpoint (from the centre of the sphere) to the radius of the sphere; A is the azimuth angle defined by the deflections from the CGI. As well as causing a curved horizon, the depression angle of a target relative to the horizon is an important range cue and therefore this distortion should not be ignored.

It can be seen that when a=0, $D_D = D_C$ and no corrections are needed. However when a becomes significant the desired depression of the deflection signal is a function of D_P, D_C, a and A in which both A and D_C may be changing rapidly at pixel rate with a rolled raster display. This correction computing needs to be studied in order to implement it in an efficient way.

Acknowledgements

The implementation of the system described in this paper was funded by the Procurement Executive, Ministry of Defence, Royal Aircraft Establishment, Farnborough.

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SESSION VI

Display Considerations
Part III

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Dr. Furness is the Chief of the Visual Display Systems Branch of the Human Engineering Division, Air Force Aerospace Medical Research Laboratory.

He received his undergraduate degree in Electronics Engineering from Duke University and Doctor of Philosophy Degree in Engineering and Applied Science from the University of Southampton, England.

Dr. Furness has been involved over the past 17 years in the development of advanced operator-centered control/displays for modern crew systems. His efforts include the development of the visually-coupled systems (helmet-mounted sight/display) and their application to visual scene simulation for training and engineering design applications.

A SECOND GENERATION WAVIDS

Arthur Cox was educated in England at the University of Newcastle-on-Tyne and at Cambridge University. He was awarded a D.Sc. degree in 1966 for his work in optics. He is a Fellow of the Institute of Physics (London), of the Optical Society of America, and of the Society of Photo-Optical Instrumentation Engineers. He is the author of A System of Optical Design (Focal Press), Photographic Optics (Focal Press), and co-author of Engineering Optics (Pitman). He was formerly President of the Optical Division of the Bell & Howell Company. He has worked as a consultant in the field of optics for major companies and for the United Nations. He is currently Vice-President of Engineering for K.F.O. Associates, Inc.

Wiley V. Dykes holds a B.S. degree from Florida State University and has completed advanced studies in Physics and Physical Sciences. He has over 28 years experience with military equipment and simulation. He is a Physical Scientist at NAVTRAEQUIPCEN and performs as Acquisition Director on various visual simulation projects, radar simulation and aerial gunnery simulation. He is currently Acquisition Director for WAVIDS which is being developed for AFHEL at Williams AFB, Arizona, by the Naval Training Equipment Center in Orlando, Florida.

A SECOND GENERATION WAVIDS

ABSTRACT A second generation WAVIDS (Wide Angle Virtual Image Display System) has been designed using Fresnel lenses. The instantaneous field of view is 75 degrees, and the total field of view is 90 degrees, with an eye-clearance of 38.0 inches. The correction of spherical aberration, coma and astigmatism leads to a design with 30% negative distortion. An auxiliary optical system has, therefore, been designed which takes an undistorted image and introduces a compensating 30% distortion. As a result an undistorted image is viewed through the WAVIDS.

INTRODUCTION A virtual image display system (VIDS) is one which allows the scene that is viewed by a pilot in a training simulator to appear as if it were at infinity. There are two obvious advantages resulting from this. The pilot's eyes are relaxed to the same state of accommodation as in actual flying, and parallax errors between the scene and the cockpit structure, as the pilot moves his head, are eliminated.

There are two principal traditional types of VIDS. The first comprises a beam-splitter and a concave mirror. The second is the "Pancake Window" of the Farrand Optical Company. A third type which has been recently developed uses Fresnel lenses as the optical components.(1) The form which this takes is shown in Figure 1. It utilizes five (5) Fresnel lenses. The chromatic correction is established by filling the space between the third and fourth elements with a suitable liquid.

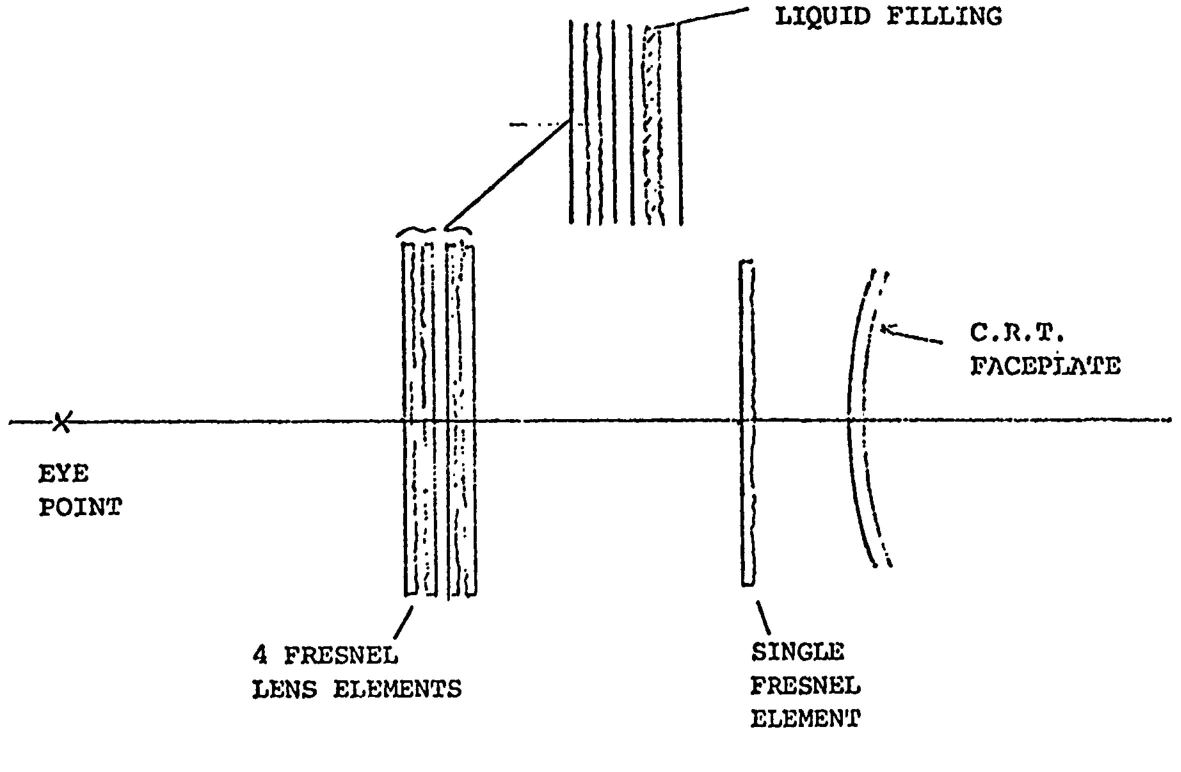

FIGURE 1.

A system of this type has been designed and fabricated. The instantaneous field of view is 48 degrees horizontal and 36 degrees vertical for a diagonal field of view of 58 degrees. The eye clearance is 24 inches, and the viewing area is a truncated 12 inch diameter circle, as shown in Figure 2. This system was designed for use with a 25 inch diagonal color TV CRT, with a curvature of 40.7 inches, as shown in Figure 1. Particular attention was paid to the correction of distortion, which was specified to be not more than 4%.

The Fresnel elements were made by diamond turning. This led to an important improvement in light transmission and the reduction of Moire effects, because it became feasible to use negative drafts or undercuts on the high-rises (non-refracting surfaces) of the Fresnel elements, as shown in Figure 3. This technique allowed the high rises to be aligned along the mean direction of the light rays.

VIDS PERFORMANCE In order to establish a standard of comparison between the VIDS and the more recent WAVIDS, a brief discussion of the VIDS performance may be given. The procurement specification called for maximum values of dipvergence and divergence/convergence for the pairs of pupil points shown in Figure 2, and for the field points shown in Figure 4. The pattern of rays, whose path was traced through the system, was matched to this set of pupil points and field points. The result of this was that the scene, as viewed through the system which was fabricated, showed a "swimming effect" that was quite disturbing. The source of this effect was established by tracing rays through the pupil points shown in Figure 5, and for field points on the axis and at off-axis distances of 4.375, 6.25, 8.75 and 12.5 inches on the face of the CRT. The path of rays was from the observer's side of the system to the CRT. Ideally, all of the rays going through the pupil that are directed towards a particular point on the CRT should meet in a point on the tube surface. Departures from this condition indicate imperfections in the system performance. Values for the VIDS are given in Table 1. This defect has been corrected in the WAVIDS, as described below.

Another defect in the VIDS, as fabricated, was that the high-rises on the Fresnel surfaces were too visible. This resulted from an arbitrary choice of .150 inches for the groove spacing. In the WAVIDS this value has been reduced to .060 inches.

(For a complete report on the VIDS see Reference 2)

WAVIDS PERFORMANCE The WAVIDS was to be one which could be used as a unit in a dodecahedron dome assembly to cover an extended field of view. For this purpose the procurement specifications called for an instantaneous field of view of 75 degrees and a total field of view of 90 degrees. (The instantaneous field of view is that which can be observed from the center of the pupil area. The total field of view is that which can be seen from the extreme edge of the pupil area). The pupil area has a diameter of 12 inches, and the eye clearance is 38.0 inches. (This duplicates the parameters of a system using Farrand Pancake Windows).

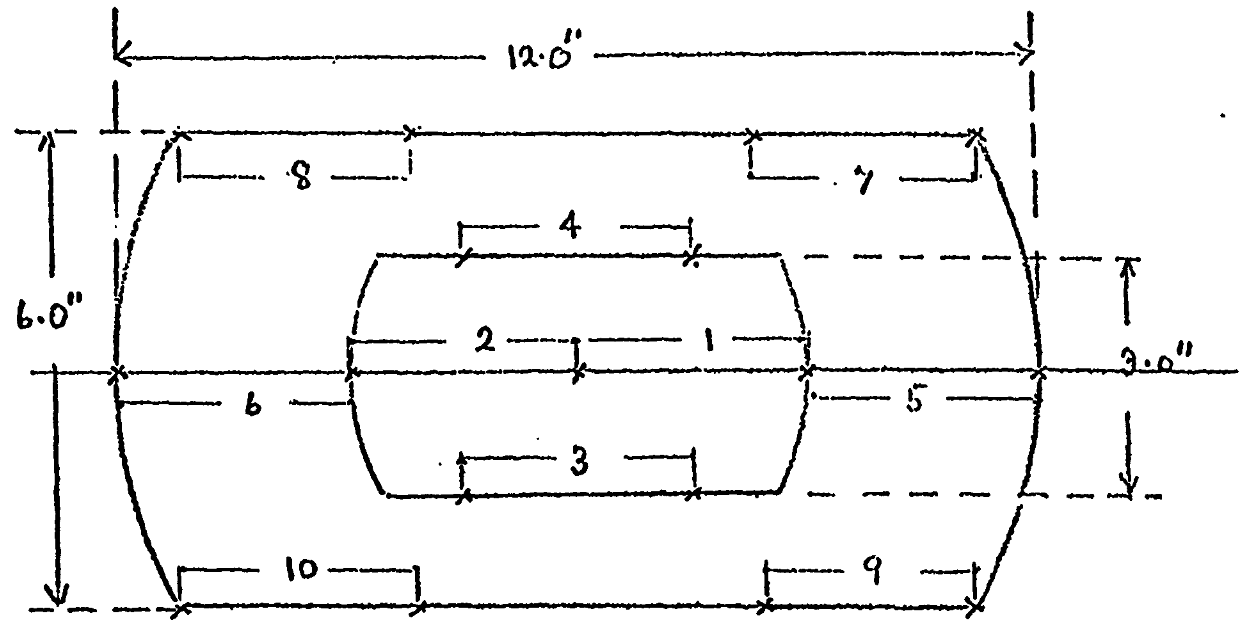

FIGURE 2.

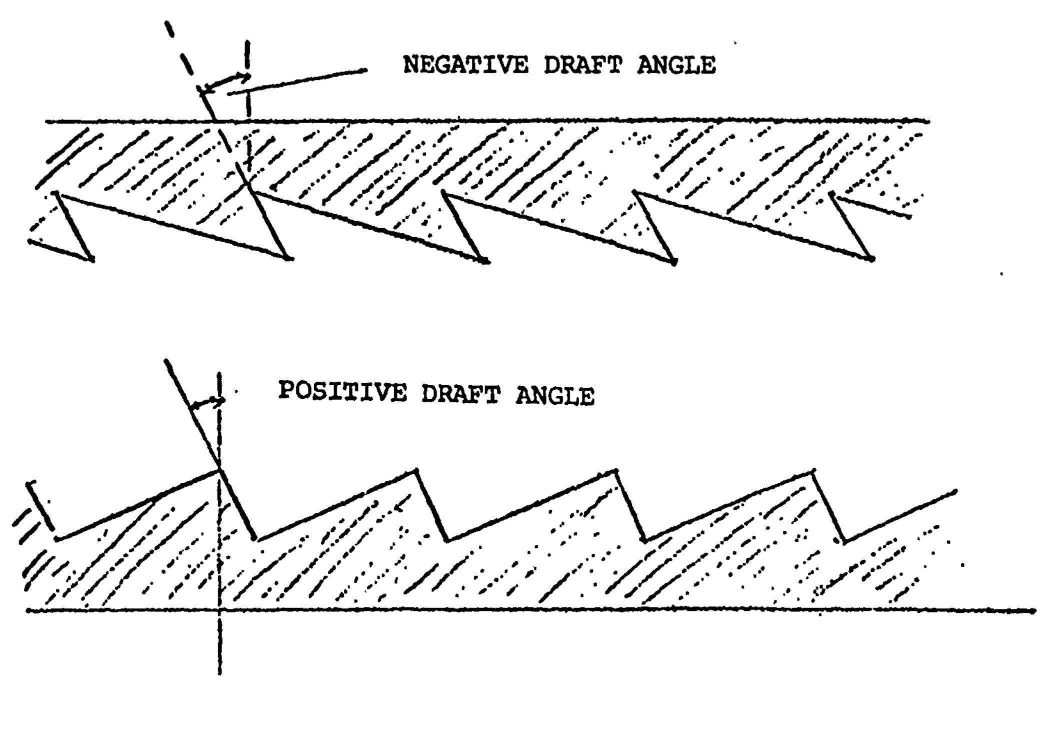

FIGURE 3.

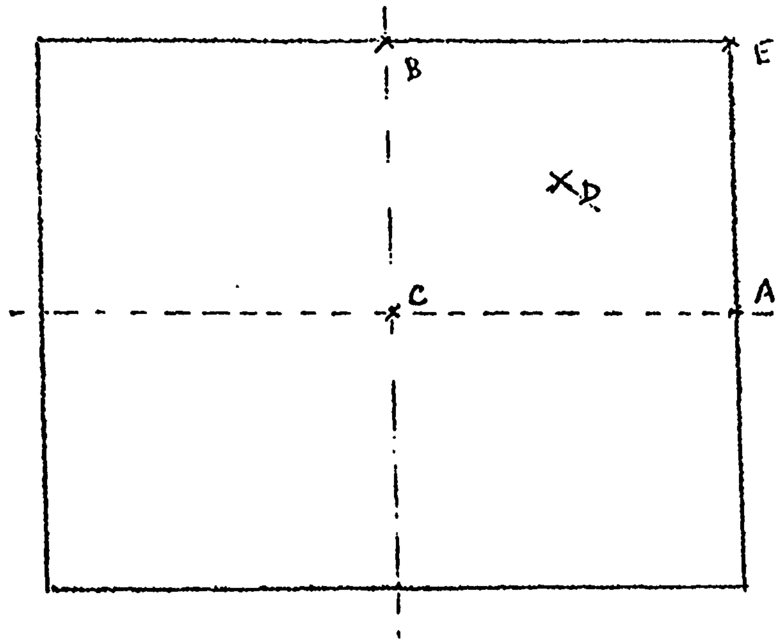

FIGURE 4.

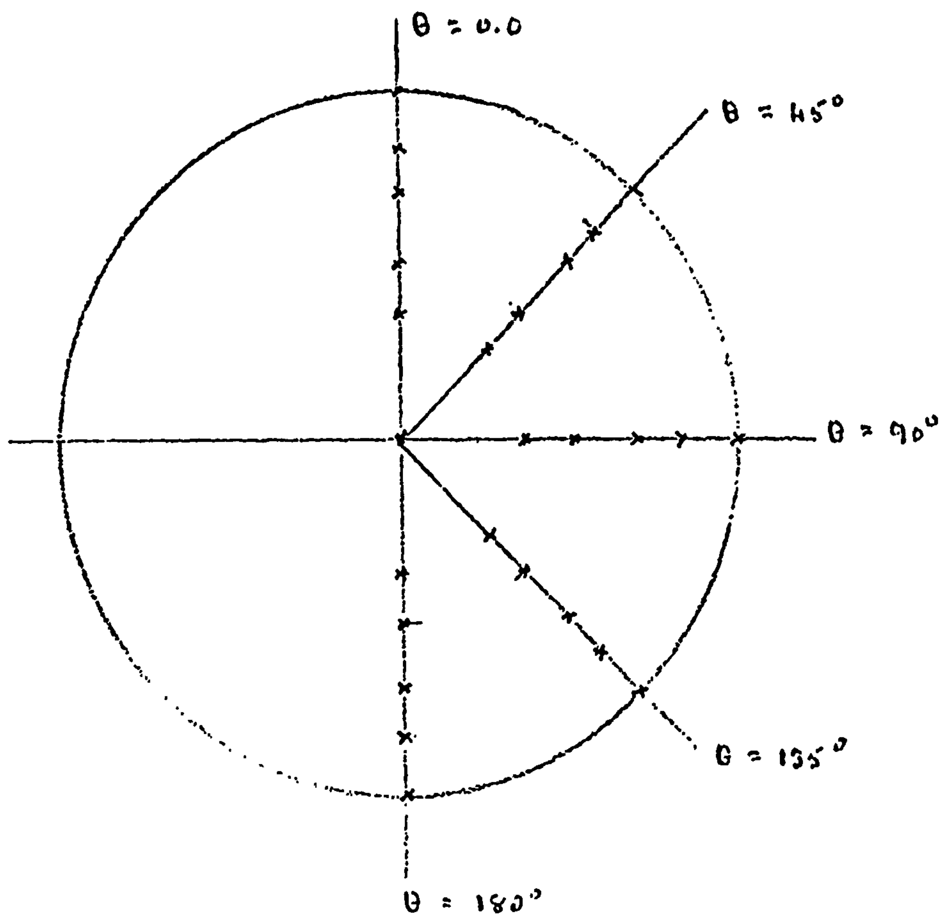

FIGURE 5.

TABLE 1.

0.0 Field	θ = 0.0		θ = 45°		θ = 90°		θ = 135°		θ = 180°	
1.0	0.0	.0304	.0215	.0215	.0304	0.0	.0215	-.0215	0.0	-.0304
.84	0.0	.0220	.0156	.0156	.0220	0.0	.0156	-.0156	0.0	-.0220
.70	0.0	.0147	.0104	.0104	.0147	0.0	.0104	-.0104	0.0	-.0147
.50	0.0	.0059	.0041	.0041	.0059	0.0	.0041	-.0041	0.0	-.0059
.35	0.0	.0022	.0015	.0015	.0022	0.0	.0015	-.0015	0.0	-.0022
.35 Field										
1.0	0.0	.3503	.0880	.2579	.0207	.0847	-.1147	.0797	0.0	.1591
.84	0.0	.3088	.0825	.2221	.0204	.0640	-.0808	.0372	0.0	.0834
.70	0.0	.2586	.0649	.1836	.0171	.0472	-.0567	.0098	0.0	.0344
.50	0.0	.1713	.0372	.1200	.0107	.0249	-.0277	-.0167	0.0	-.0144
.35	0.0	.1102	.0204	.0768	.0067	.0127	-.0124	-.0239	0.0	-.0296
.50 Field										
1.0	0.0	.3083	.0805	.2931	.0017	.0961	-.1620	.0281	0.0	.0947
.84	0.0	.3587	.0759	.2731	.0110	.0738	-.1116	-.0192	0.0	.0070
.70	0.0	.3220	.0651	.2389	.0130	.0550	-.0766	-.0461	0.0	-.0438
.50	0.0	.2345	.0406	.1693	.0109	.0294	-.0358	-.0642	0.0	-.0823
.35	0.0	.1612	.0234	.1150	.0080	.0151	-.0159	-.0605	0.0	-.0851
.7 Field										
1.0	0.0	.2393	.0021	.2234	-.0548	.0778	-.2079	-.1064	0.0	-.1125
.84	0.0	.2940	.0258	.2499	-.0255	.0631	-.1409	-.1414	0.0	-.1818
.70	0.0	.3029	.0319	.2439	-.0110	.0486	-.0954	-.1532	0.0	-.2091
.50	0.0	.2593	.0260	.1970	-.0003	.0268	-.0441	-.1424	0.0	-.2017
.35	0.0	.1963	.0165	.1448	.0019	.0140	-.0200	-.1153	0.0	-.1647
1.0 Field										
1.0	0.0	.4863	-.1695	.0592	-.2552	-.0289	-.2752	-.2641	0.0	-.4492
.84	0.0	.1843	-.1275	.0322	-.1767	-.0123	-.1849	-.2575	0.0	-.4325
.70	0.0	.0973	-.0929	.0432	-.1274	-.0046	-.1314	-.2349	0.0	-.3887
.50	0.0	.0795	-.0514	.0654	-.0735	.0005	-.0710	-.1775	0.0	-.2851
.35	0.0	.0810	-.0310	.0666	-.0462	.0009	-.0412	-.1256	0.0	-.1963

The full field covered has a radius of 12.5 inches. The values of θ are shown in Figure 5. The values 1.0, .84, etc. refer to the pupil points shown in Figure 5. The first column under each value of θ is the x-component of the image displacement in the focal plane, and the second column is the y-component. Dimensions are in inches.

It was not possible, from the point of view of practical optical design, and with these parameters, to use a 25 inch CRT (this would imply a focal length of 16.3 inches for the Fresnel system, and a much more complicated system of Fresnel lens elements). For this reason it was proposed that the WAVIDS should be used to view an image projected upon a screen mounted in its focal plane.

The design of the WAVIDS was carried out with this in mind, and in the light of experience gained with the VIDS advantage was taken of this situation to concentrate attention on the correction of spherical aberration, coma and astigmatism over the whole 12 inch diameter pupil area. The basic form of system shown in Figure 1 was retained.

For purposes of comparison with the VIDS performance, the values given in Table 2 show the transverse aberrations in the image plane of the WAVIDS, reduced to the same scale as those given for the VIDS in Table 1. There is a major reduction in the values of these aberrations, and no swimming effect is anticipated.

The chromatic effects have been evaluated in terms of the angular spread between light for the C and F spectral lines, as seen by the observer. The maximum angular spread is 7.4 minutes of arc (approximately 2 milli-radians). It is not expected that this will result in any significant degradation of image quality.

In using visual systems with binocular viewing it is essential to meet strict requirements on dipvergence and on divergence/convergence, so that no eye fatigue is induced. In the case of the VIDS the dipvergence and divergence were calculated for the sets of pupil points shown in Figure 2 and for the field points shown in Figure 4. A change has to be made for the WAVIDS, particularly when it is used in a dodecahedron assembly, because we then have two separate cases to consider:

a) Both eyes are viewing an element of the scene through the same Fresnel system;

b) One eye is viewing an element of the scene through one Fresnel system, while the other eye is viewing the same element through an abutting system.

The situation which prevails in a dodecahedron assembly is shown in Figure 6, where two neighboring Fresnel systems, each of pentagonal contour, abut along the line AA'. The instantaneous field of view is shown by the circumscribing circle about each pentagon.

Dipvergence and divergence/convergence, for the case where both eyes are viewing the scene through the same Fresnel system, have been evaluated for the field points 0-6, in Figure 6, using the pupil point pairs of Figure 2. Results are given in Table 3.

TABLE 2.

0.0 Field	θ = 0.0		θ = 45°		θ = 90°		θ = 135°		θ = 180°	
1.0	0.0	-.0037	-.0026	-.0026	-.0037	0.0	-.0026	.0026	0.0	.0037
.84	0.0	.0136	.0097	.0097	.0136	0.0	.0097	-.0097	0.0	-.0136
.70	0.0	.0215	.0152	.0152	.0215	0.0	.0152	-.0152	0.0	-.0215
.50	0.0	.0232	.0164	.0164	.0232	0.0	.0164	-.0164	0.0	-.0232
.35	0.0	.0192	.0136	.0136	.0192	0.0	.0136	-.0136	0.0	-.0192
.35 Field										
1.0	0.0	-.0485	.0010	-.0519	.0034	-.0525	.0051	-.0541	0.0	-.0560
.84	0.0	-.0212	.0121	-.0260	.0188	-.0368	.0152	-.0488	0.0	-.0545
.70	0.0	-.0036	.0169	-.0101	.0252	-.0255	.0192	-.0417	0.0	-.0491
.50	0.0	.0097	.0176	.0031	.0256	-.0129	.0187	-.0296	0.0	-.0368
.35	0.0	.0122	.0144	.0068	.0207	-.0063	.0150	-.0198	0.0	-.0254
.50 Field										
1.0	0.0	-.0744	-.0013	-.0746	.0046	-.0702	.0102	-.0680	0.0	-.0700
.84	0.0	-.0408	.0099	-.0440	.0190	-.0494	.0213	-.0568	0.0	-.0617
.70	0.0	-.0196	.0150	-.0241	.0250	-.0342	.0213	-.0458	0.0	-.0541
.50	0.0	-.0010	.0166	-.0057	.0251	-.0174	.0196	-.0299	0.0	-.0361
.35	0.0	.0053	.0135	.0013	.0202	-.0085	.0152	-.0188	0.0	-.0233
.7 Field										
1.0	0.0	-.0932	-.0119	-.0978	-.0043	-.0860	.0136	-.0659	0.0	-.0608
.84	0.0	-.0618	0.0	-.0652	.0102	-.0605	.0189	-.0508	0.0	-.0558
.70	0.0	-.0400	.0066	-.0427	.0169	-.0419	.0199	-.0382	0.0	-.0378
.50	0.0	-.0174	.0102	-.0193	.0187	-.0213	.0172	-.0221	0.0	-.0228
.35	0.0	-.0067	.0094	-.0081	.0155	-.0104	.0129	-.0123	0.0	-.0131
1.0 Field										
1.0	0.0	.0325	-.0271	-.0200	-.0360	-.0849	-.0022	-.0672	0.0	-.0476
.84	0.0	.0315	-.0166	-.0093	-.0191	-.0597	.0023	-.0519	0.0	-.0388
.70	0.0	.0274	-.0097	-.0028	-.0092	-.0415	.0040	-.0397	0.0	-.0313
.50	0.0	.0198	-.0033	.0027	-.0013	-.0212	.0042	-.0244	0.0	-.0214
.35	0.0	.0138	-.0006	.0043	.0011	-.0141	.0031	-.0150	0.0	-.0145
Total Field										
1.0					-.0763	-.1367	-.0248	-.0480	0.0	-.0651
.84					-.0532	-.0938	-.0174	-.0207	0.0	-.0392
.70					-.0378	-.0638	-.0126	.0011	0.0	-.0153
.50					-.0220	-.0318	-.0079	.0257	0.0	.0173
.35					-.0136	-.0154	-.0055	.0359	0.0	.0356

Only the sagittal and lower rim rays are relevant for the total field. See also the note to Table 1. The undistorted instantaneous field radius is 18.42".

TABLE 3.

Group	FP0	FP1	FP2	FP3	FP4	FP5	FP6	
1	0.0	0.0	2.52	3.06	2.15	0.0	1.24	DIP
	3.33	-2.53	-1.54	2.63	3.68	1.37	1.83	DIV/CON
2	0.0	0.0	.15	3.06	2.15	0.0	.87	" "
	3.33	3.20	3.78	2.63	3.68	5.25	5.03	" "
3	0.0	.50	1.12	0.0	0.0	3.86	.14	" "
	3.92	.53	1.28	3.69	4.39	-.72	3.78	" "
4	0.0	.50	1.28	0.0	0.0	3.86	.23	" "
	3.92	.53	1.61	2.65	4.09	-.72	3.95	" "
5	0.0	0.0	4.43	9.32	6.58	0.0	3.23	" "
	-3.85	-10.78	-10.61	-3.31	-3.03	-9.49	-7.81	" "
6	0.0	0.0	3.59	9.32	6.58	0.0	3.23	" "
	-3.85	5.42	4.71	-3.31	-3.03	2.81	1.74	" "
7	2.96	2.78	5.42	9.11	7.92	2.86	5.40	" "
	-2.43	-9.07	-7.16	-7.53	-1.88	-6.51	-5.53	" "
8	2.96	1.10	4.73	9.61	7.92	2.60	5.28	" "
	-2.43	4.43	3.79	-7.50	-1.88	3.00	2.04	" "
9	2.96	2.78	1.77	5.89	2.78	2.86	.10	" "
	-2.43	-9.07	-9.88	-5.63	-1.42	-6.51	-5.86	" "
10	2.96	1.10	0.79	5.89	2.78	2.60	.05	" "
	-2.43	4.43	4.49	-5.63	-1.42	3.00	2.31	" "

Dipvergence and Divergence/Convergence are given in minutes of arc for the field points shown in Figure 5 and for the pairs of pupil points shown in Figure 2.

TABLE 4.

Group	FPA	FPB	FPC	
1S	0.0	1.0	.9	DIP
	-2.6	.7	-2.0	DIV/CON
2S	0.0	1.5	.2	" "
	2.1	2.1	2.1	" "
3S	0.0	1.1	.2	" "
	-0.1	3.8	.2	" "
4S	1.8	2.6	1.3	" "
	-3.1	3.2	-0.9	" "
5S	.5	3.7	.1	" "
	3.1	4.5	2.3	" "
6S	1.2	3.1	1.2	" "
	-0.7	4.1	.8	" "
7S	1.8	.5	.6	" "
	-3.1	2.7	-4.0	" "
8S	-0.5	.4	.2	" "
	1.5	.9	.8	" "

Dipvergence and divergence/convergence are given in minutes of arc for the field points shown in Figure 5 and for the pupil points shown in Figure 6.

TABLE 5.

Ideal Image Position	Fresnel Image Position	System Image Position
3.80"	3.783"	3.778"
7.60	7.466	7.431
11.40	10.955	10.862
15.20	14.169	14.011
19.00	17.049	16.862
22.80	19.560	19.414
26.60	21.724	21.663
30.40	23.587	23.590
34.20	25.226	25.181
38.80	26.486	26.444

The limiting value of the ideal image position corresponds to a total field angle of 45 degrees.

The maximum deviation, for an ideal pupil height, is .187"; with a focal length for the Fresnel system of 38.0", this gives an image pointing error of 5 milli-radians.

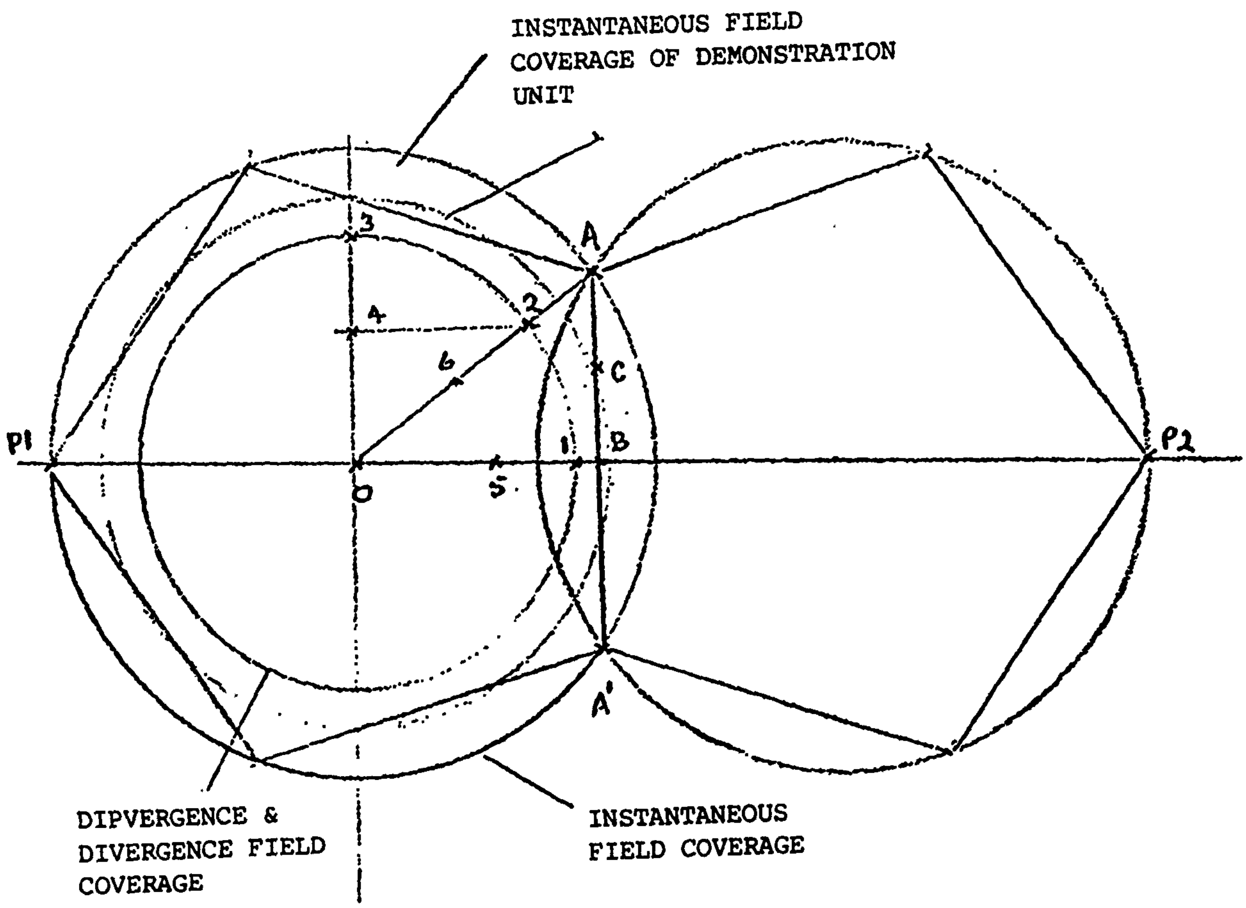

FIGURE 6.

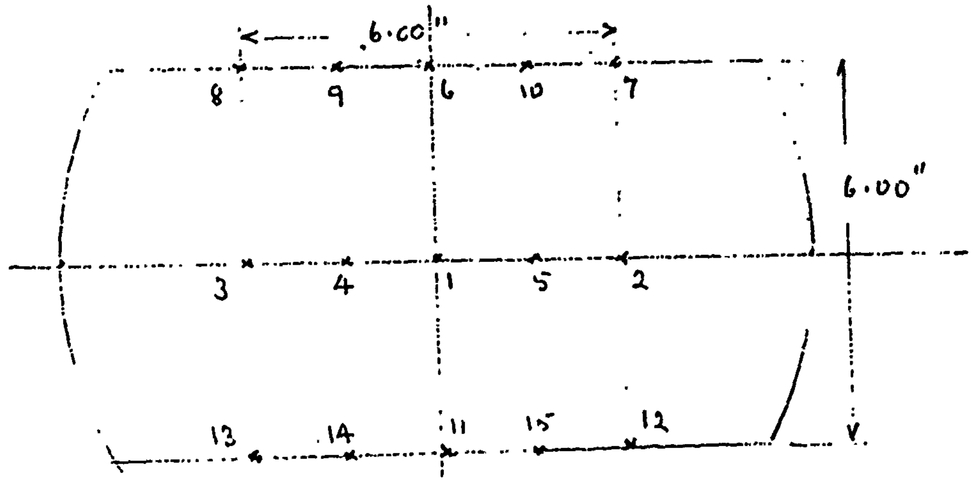

FIGURE 7.

Along the line AA', where the two eyes are looking at the same scene element through adjacent Fresnel systems, the dipvergence and divergence/convergence have been evaluated for the field points A, B and C using the pupil points shown in Figure 7. Results are given in Table 4.

The dipvergence and divergence/convergence reported in Table 4 can also be interpreted as the maximum image jump which will take place when the line of sight moves from one Fresnel system to the adjoining system.

IMAGE DISTORTION AND CORRECTION The price that has to be paid for the standard of correction which has been established, and for the angular field which is covered, is the introduction of heavy negative distortion, amounting to approximately 30% at the limits of the total field of view. An auxiliary optical system has, therefore, been designed which will take the undistorted output of a projector, such as a G.E. light valve, and introduce a compensating distortion in the image which it forms in the focal plane of the Fresnel lens system. In this way an undistorted image is viewed through the WAVIDS.

This auxiliary optical system serves a further purpose also. There are occasions when it is necessary to have the central ray of a projected bundle of rays pointing upwards or downwards at an angle exceeding that allowed for the G.E. light valve. Bending of the optical axis to produce this pointing direction, while maintaining the light valve in a horizontal position, can be accomplished by using mirrors in the auxiliary optical system.

The form of system which was developed for this purpose is shown in Figure 8. This system mounts directly in front of the projection lens of the G.E. light valve (or equivalent slide projector). It has an overall length of approximately 36.0 inches, with an air space of sufficient length to permit the insertion of mirrors to bend the optical path. The distance from the exit face of the system to the screen in the focal plane of the Fresnel system is approximately 56.0 inches. This system uses three aspheric surfaces, which are identified in Figure 8.

The effectiveness of the distortion correction may be judged from the values given in Table 5. In the first column are given the values in the focal plane of the Fresnel lens system which would correspond to a distortion-face system. In the second column are given the actual values which are obtained because of the heavy distortion in the system. In the third column are given the positions of the image points produced by the distortion correcting system. (All values are in inches and give the distances of image points from the center of the field of view. This is also the center of the screen in the focal planes of the Fresnel system.)

IMAGE BRIGHTNESS In order to produce the brightest image possible the screen, which is mounted in the focal plane of the Fresnel lens system, comprises a high gain diffusing screen together with a secondary Fresnel lens. The function of the latter is to bend the light rays coming from the distortion correcting system, so that, in the absence of any diffusion, the central ray of that bundle will pass through the center of the 12 inch

diameter viewing area. Without diffusion the other rays in the bundle emerging from the distortion correcting system would not fill the complete 12 inch diameter viewing area.

The G.E. light valve which may be used with this complete system has a specified light output of 2000 lumens with an open gate, and typically 1300 lumens with TV modulation. This output is obtained with a 4:3 oil film format. Since we propose to use only the inscribed circle in this area, the light output is reduced by a factor of .59, giving values of 1180 lumens for an open gate and 767 lumens for a TV modulated output.

Because of the distortion introduced into the systems this light falls into a circular area with a diameter of 54 inches. The central illumination of this area, however, corresponds to the case where the light patch has a diameter of 76 inches. Using the latter as a conservative value, and assuming that there is no loss in the distortion correcting system, for a screen gain of unity, the brightness of the screen is 37.5 foot-lamberts for an open gate and 24.3 foot-lamberts for TV modulation. Assuming a reasonable value of 85% transmission for the distortion correcting system the respective values become 31.8 and 20.6 foot-lamberts respectively.

The apparent brightness of the image as it is viewed through the Fresnel lens system is decreased by these factors:

a). Absorption in the Fresnel lens material;
b). Surface reflection losses;
c). Loss due to the Fresnel lens structure.

The total thickness of all five Fresnel elements is approximately 2.5 inches (6.25 cm.). No precise figures are available for the absorption loss per cm. of the optical path, but it is safe to set an upper limit of 1% per cm. The total absorption loss should, therefore, not exceed 6.5%.

The reflection loss for normal incidence for an uncoated surface of a Fresnel element is 4%. With a single layer of magnesium fluoride this can be reduced to 1.52%. The plane and Fresnel surfaces will be coated with a single layer of magnesium fluoride. In the worst case, with only the plane surfaces coated the reflection loss will be 19.5%. With all surfaces coated this will be reduced to 12.0%.

The loss due to the geometric structure of the Fresnel grooves will be comparable with that measured for the VIDS system, namely 15%.

Taking the worst case, the transmission factor for the Fresnel system will be 64%.

For a screen gain of unity we, therefore, arrive at brightness levels of 24.0 foot-lamberts for an open gate and 15.6 foot-lamberts for a TV modulated gate.

In practice we propose to use a high gain screen, with a gain of approximately 5. This will give overall brightness levels of 120 foot-

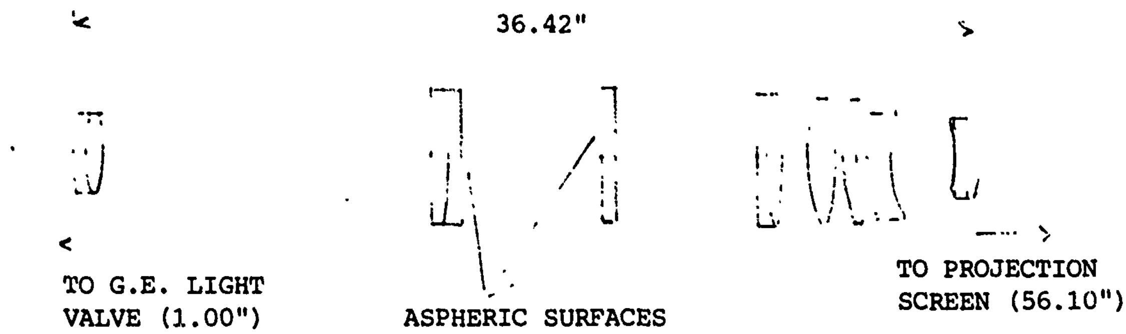

FIGURE 8.

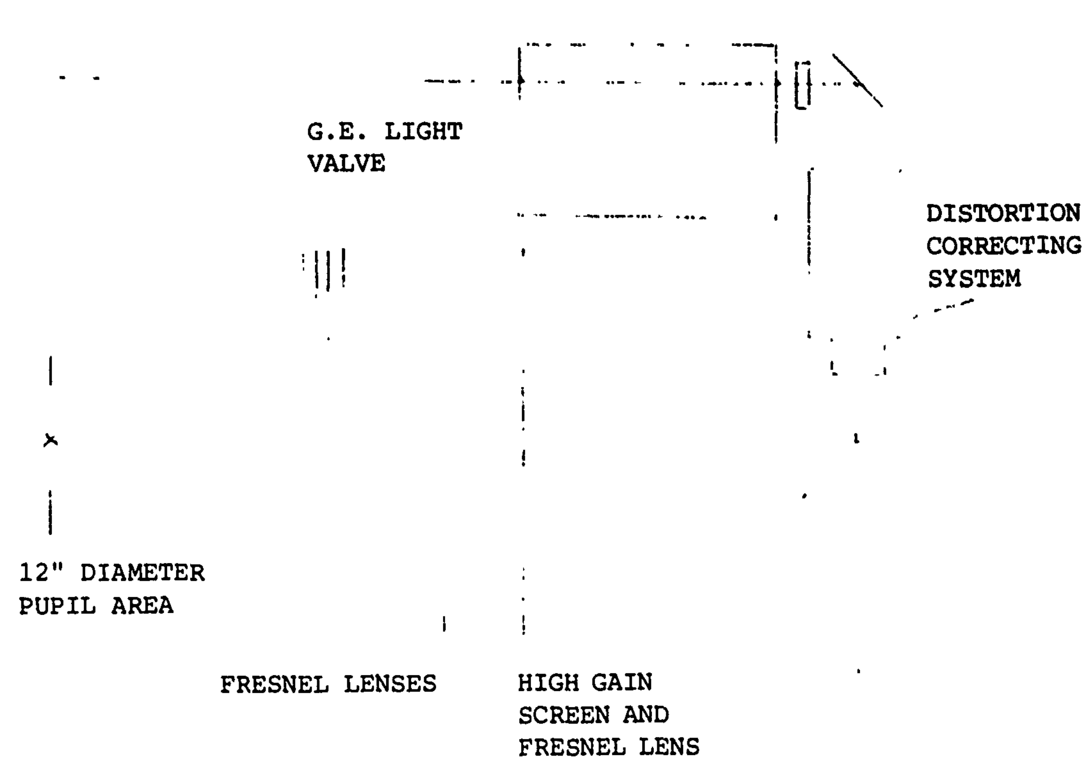

FIGURE 9.

lamberts and 78 foot-lamberts. This seems to be an adequate brightness level.

DEMONSTRATION UNIT Because of current limitations on the manufacturing capabilities of Fresnel lenses, a demonstration unit has been made using Fresnel elements having a clear aperture of 48 inches. This gives an instantaneous field of view of 63 degrees and a total field of 75 degrees. This unit will serve to give very strong indications that the reasoning behind the approach adopted for the WAVIDS is sound.

SUMMARY This Fresnel system readily lends itself to mounting in a dodecahedron assembly, with minimum gaps between neighboring systems, so that a field which approaches or exceeds a hemisphere may be covered. The aberrational correction is such that no problems are expected across the interface between adjoining systems.

If a brightness level lower than that quoted can be accepted, then alternative projection systems may be used, including high resolution monitors in which the distortion correction may be achieved by raster correction.

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THE EFFECTS OF TIME DELAY IN MAN-MACHINE CONTROL SYSTEMS: IMPLICATIONS FOR DESIGN OF FLIGHT SIMULATOR VISUAL-DISPLAY-DELAY COMPENSATION

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THE EFFECTS OF TIME DELAY IN MAN-MACHINE CONTROL SYSTEMS:
IMPLICATIONS FOR DESIGN OF FLIGHT SIMULATOR VISUAL-DISPLAY-DELAY COMPENSATION

ABSTRACT

When human operators are performing precision tracking tasks, their dynamic response can often be modeled by quasi-linear describing functions. That fact permits analysis of the effects of delay in certain man-machine control systems using linear control system analysis techniques. The analysis indicates that a reduction in system stability is the immediate effect of additional control system delay, and that system characteristics moderate or exaggerate the importance of the delay. A selection of data (simulator and flight test) consistent with the analysis is reviewed. Flight simulator visual-display-delay compensation, designed to restore pilot-aircraft system stability, was evaluated in several studies which are reviewed here. The studies range from single-axis, tracking-task experiments (with sufficient subjects and trials to establish the statistical significance of the results) to a brief evaluation of compensation of a computer-generated-imagery (CGI) visual display system in a full six-degree-of-freedom simulation. The compensation was effective — improvements in pilot performance and workload or aircraft handling-qualities rating (HQR) were observed. Results from recent aircraft handling-qualities research literature, which support the compensation design approach, are also reviewed.

INTRODUCTION

Time-delay in man-machine control systems is an important issue because of recent developments in flight simulation technology and in aircraft control system technology. In flight simulation, there is a trend toward the use of computer-generated imagery (CGI) systems to generate out-the-window visual scenes. CGI visual systems offer important advantages, including large field of view, ease of scene modification, and independent motion of scene elements such as combat targets. CGI systems construct an image from a description of the scene stored in a computer. The image construction time, though short (~100 msec), introduces a delay into the pilot-aircraft system. Several authors (refs. 1-3) have traced simulation problems such as — unrealistic pilot-induced-oscillation (PIO) tendencies when performing precision maneuvers — to time-delay in visual system cueing.

There is also a trend toward use of complex control systems in modern aircraft in an attempt to improve the performance or reduce the cost of these aircraft. The elements of these control systems (e.g., prefilters, samplers, computers, stability augmentation system filters, smoothing filters) may introduce as much as several hundred milliseconds of "equivalent delay" (ref. 4). Serious flying-qualities problems of early versions of the Space Shuttle (ref. 5) and other (ref. 4) aircraft have been attributed to these delays.

The primary interest here is the design of compensation for flight simulator visual-display delay. To that end, we first review an analysis of time-delay in linear control systems and data (simulator and flight test) that support use of the linear analysis in the study of delay in certain man-machine control systems. Next, an approach to compensation for delay in linear control systems is reviewed and modifications required to adapt the procedure to compensate for simulator visual-display-delay are described. Flight-test data, which provide important support for the compensation approach, are noted. Finally, several studies that evaluated compensation effectiveness are reviewed. The studies range from single-axis,

tracking-task experiments (with sufficient subjects and trials to establish the statistical significance of the results) to a brief evaluation of compensation of a CGI visual-display system in a full six-degree-of-freedom simulation.

EFFECTS OF TIME-DELAY IN MAN-MACHINE CONTROL SYSTEMS

The effects of time-delay in linear, closed-loop control systems can be readily determined by conventional control system design methods. Figure 1a is a block diagram of a simple (unmanned) control system; figure 1b is a sketch of the amplitude and phase response of the open-loop system (c/e). Figure 1b identifies two important system parameters: crossover frequency (ω_c) and phase margin (ϕ_m'). Crossover frequency is that frequency at which the transfer function amplitude ratio "crosses" from greater than unity to less than unity (i.e., crosses the zero decibel line). Crossover frequency is a measure of system bandwidth or responsiveness. Phase margin is defined as the amount by which the system phase angle at ω_c exceeds -180°. Phase margin is a measure of system stability in situations of primary interest here (ref. 6). Figure 1b also illustrates the change in the system open-loop transfer function when a delay is inserted into the system. The delay transfer function G_D has an amplitude ratio that is identically 1 and a phase given by the expression $\phi_d = -\omega t_d$ (where ω is frequency and t_d is the delay). The effect of the delay is to decrease the phase margin and stability of the system.

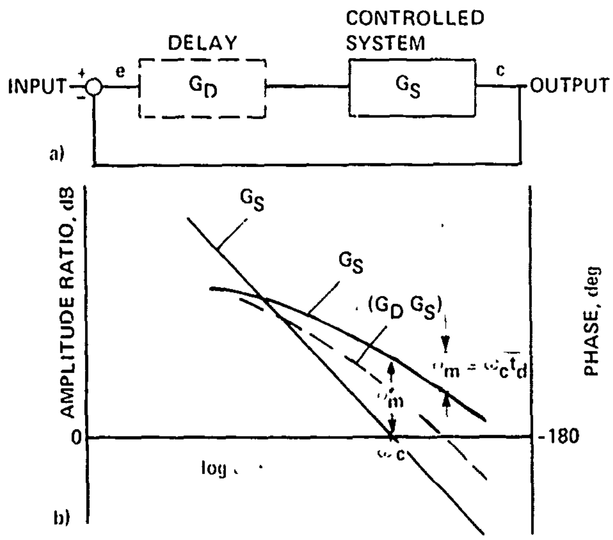

Figure 1.- Closed-loop control system. a) System diagram. b) Amplitude ratio and phase response of the open-loop system (c/e).

McRuer and Krendel (ref. 7) and others have shown that pilots performing precision tracking tasks can often be modeled as quasi-linear describing functions. That fact suggests that the preceding analysis of delay effects might be extended to certain man-machine control systems. A selection of simulator and aircraft flight-test data that support the extension are reviewed next.

Crane (ref. 8) applied the linear system analysis to the pilot-aircraft system and documented (for a single-axis tracking task) the change in pilot performance and dynamic response and the change in pilot-aircraft system stability for a range of visual-display delays. The consistence of that data indicated that the analysis was reasonable. Extrapolating the data from that study, Crane concluded that when a simulator pilot was performing a precision maneuver

> . . . delay in the visual display of aircraft response to pilot control input has a number of deleterious effects. The immediate effect of the delay is to decrease the stability of the pilot-aircraft system . . . . Simultaneously, pilot dynamic response and system performance change as the pilot attempts to compensate for the decrease in system stability. More importantly, the changes in pilot dynamic response and system performance can bias the results of the simulation by influencing the

pilot's rating of the handling qualities of the simulated aircraft. The decrease in system phase margin ($\Delta\phi_m$) is given by the product of the system crossover frequency (ω_c) and display delay (t_d), ($\Delta\phi_m = \omega_c t_d$). The importance of a delay increases with the ratio of (the resulting) $\Delta\phi_m$ to ϕ_m', the design phase margin. Since ω_c and ϕ_m' are dependent on the specifics of a simulation (aircraft dynamics, display, controller, task, etc.), the importance of a particular delay also depends on the simulation specifics. A given delay will be most troublesome when a pilot is attempting to precisely control a responsive aircraft (high ω_c) and when the design phase margin of the pilot-aircraft system, ϕ_m', is relatively small.

The ratio $\omega_c t_d/\phi_m'$ is called the trouble index (TI) (ref. 9). because the reduction in system stability due to delay is proportional to TI. The TI emphasizes the fact that system characteristics (ω_c,ϕ_m') moderate or exaggerate the importance of a given delay.

Relevant aircraft flight-test data are reviewed next. The variation of aircraft handling-qualities ratings (HQR) with delay and bandwidth predicted by the linear system analysis has been observed in recent studies of the effects of delay in aircraft control systems. Figure 2 (reproduced from ref. 10) summarizes data from several sources. The data exhibit the predicted degradation of HQR with delay and bandwidth.

The report (fig. 3) of Berry et al. (ref. 5), that pilots were more sensitive to control system delay when performing tasks that were relatively more stressful is also consistent with the linear system analysis. In the high stress "spot landing" task, to exercise more precise control as required by the task, the pilot must increase his gain (definition of precise control) which directly increases ω_c and TI.

The flight-test data summarized by the Wood and Hodgkinson (ref. 11) "envelopes of maximum unnoticeable added dynamics" discussed in the next section) are also consistent with the linear analysis.

The preceding discussion indicates that linear control system analysis methods can often be extended to analysis of the effects of delay in flight simulators or aircraft control systems. Adaptation of linear control system compensation techniques to compensate for simulator visual-display delay is described in the next section.

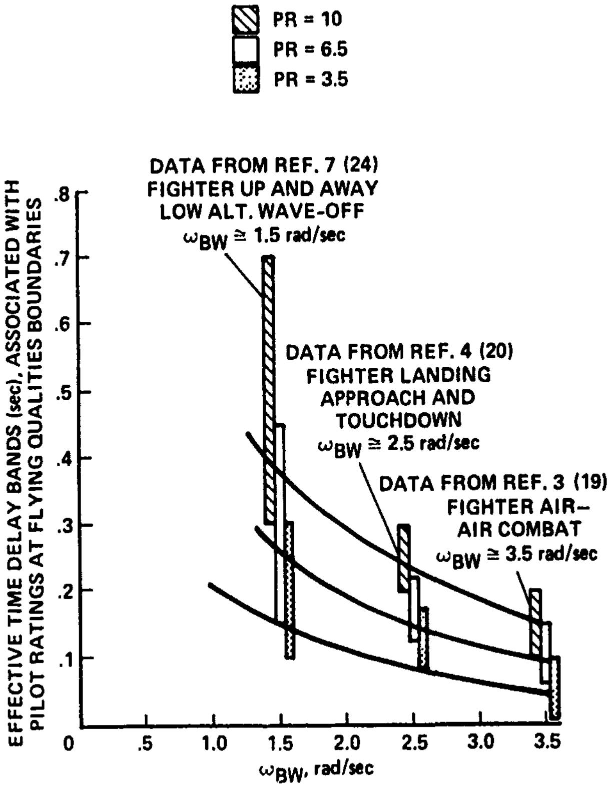

Figure 2.- Time-delay bands associated with flying-qualities boundaries versus bandwidth (from ref. 10).

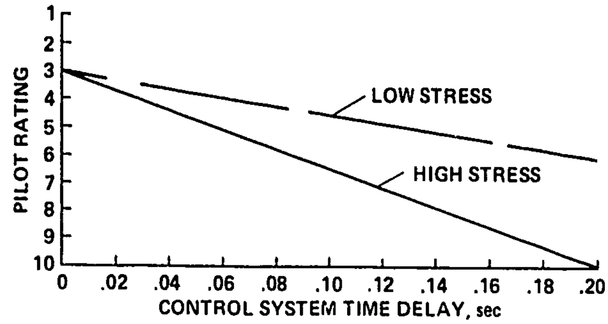

Figure 3.- Pilot rating trends for low-lift/drag ratio landings; high stress landing were "spot" landings from a lateral-offset approach (reproduced from ref. 5).

FLIGHT SIMULATOR VISUAL-DISPLAY-DELAY COMPENSATION

Several approaches to design of visual-display-delay compensation have been proposed. Ricard and Harris (refs. 12 and 13) reported the results of an evaluation of a large number of visual-display-delay compensation filters. The lead-time-constant of each of the filters was set equal to the display delay — a constraint that limits the applicability of that data (ref. 14). Compensation, very different from that recommended here, was designed using an optimal control model (ref. 15) but was not experimentally evaluated. Crane (ref. 14) applied classical linear control system design principles to the pilot-aircraft system to guide selection of compensation for visual-display delay. A review of the compensation design procedure follows.

First consider compensation for delay in the (unmanned) control system diagrammed in figure 4a. The amplitude and phase response of the lead filter G_f [eq. (1)] are sketched in figure 5.

$$G_f = K_D(T_z S + 1)/(T_p S + 1) \tag{1}$$

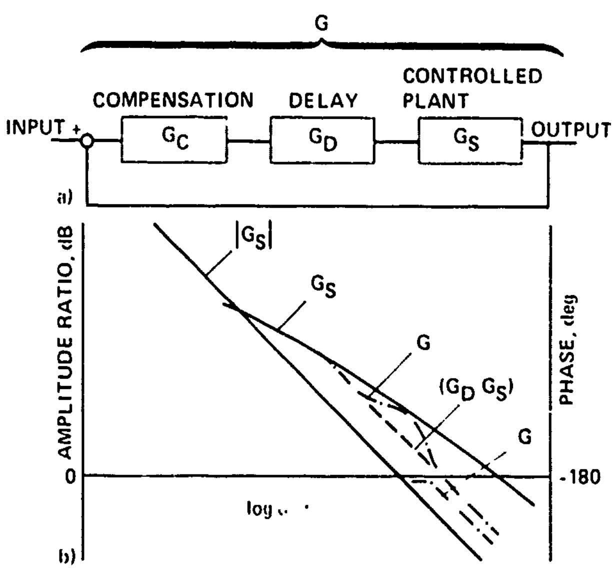

Figure 4.- Closed loop control system compensation. a) System diagram. b) Delay compensation using a lead filter.

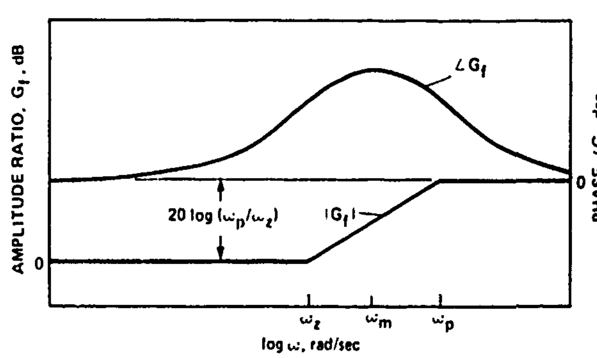

Figure 5.- Lead-filter amplitude and phase response.

The filter amplitude ratio and phase are functions of frequency and filter pole-zero separation. The filter "gain distortion," defined (ref. 9) as the ratio $|G_f(\omega_p)|/|G_f(\omega_z)|$ is also proportional to filter pole-zero separation. It is important to note that phase lead is purchased at the cost of gain distortion.

When the system transfer function is known, design of a lead filter to compensate for a specific delay, t_d, is straightforward. One need only locate the filter zero at ω_c and solve for T_p from equation (2), which equates the filter phase lead (ϕ_f) at ω_c to the delay phase lag at ω_c:

$$\phi_f\Big|_{\omega=\omega_c} = \tan^{-1} \omega_c T_z - \tan^{-1} \omega_c T_p = \omega_c t_d \tag{2}$$

Figure 4b illustrates the design. This approach restores system stability while maintaining system accuracy (proportional to system gain) and responsiveness (proportional to ω_c). The resulting increase in system gain at frequencies $>\omega_c$ is usually not a problem in unmanned systems, because system amplitude ratio and input and disturbance signal power usually decrease rapidly at frequencies $>\omega_c$.

The goal of flight-simulator visual-display-delay compensation is to restore pilot performance and dynamic response (workload) measures and pilot-aircraft system stability and responsiveness measures to values achieved when there is no delay. The approach is to

(1) Attempt to restore system stability while minimizing compensation-filter gain-distortion by providing the minimum lead required and by locating the lead at the frequency (ω_c) at which the lead will be most effective.

(2) Distribute the attendant system gain distortion (over frequency) so as to minimize (trade-off) gain-distortion effects on system responsiveness, pilot workload, tracking accuracy, display quality, and gain margin.

Important support for this approach to simulator visual-display-delay compensation can again be found in published accounts of aircraft handling qualities research. During investigations of the handling qualities of highly augmented aircraft, many researchers (refs. 16-18) have considered the question "How can one construct a low-order representation of aircraft dynamics equivalent, with regard to HQR, to a more complex high-order representation?" Wood and Hodgkinson (ref. 11) examined pilot rating differences between pairs of configurations from previous "in-flight simulator" (NT-33) data (refs. 19 and 20). Each pair of configurations consisted of an unaugmented, low-order response and a high-order system formed by adding terms to the low-order response. Wood and Hodgkinson summarized the pilot-rating data with envelopes of "maximum unnoticeable added dynamics." Figure 6 is reproduced from reference 21, where it was observed that the data show that "pilots were most sensitive to changes in the dynamics in the region of crossover."

The display-delay compensation approach attempts to minimize change in pilot-aircraft dynamics in the region of crossover in order to restore system stability and maintain system responsiveness (ref. 8). The Wood and Hodgkinson (ref. 11) data imply that approach is required to

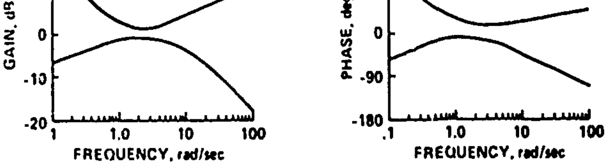

Figure 6.- Envelopes of maximum unnoticeable added dynamics (from ref. 11, reproduced from ref. 21).

minimize bias in HQR caused by delay or delay compensation. Linear control system analysis explains the sensitivity of HQR to change in aircraft dynamics in the region of crossover and further suggests that the Wood and Hodgkinson envelopes should be considered functions of the system characteristics (ω_c, ϕ_m') of particular aircraft rather than absolute "maximums." Experimental evaluations of compensation effectiveness are described next.

COMPENSATION EVALUATION EXPERIMENTS

Oscilloscope Display: Single-Axis Tracking Task

The tracking task used in the first experimental evaluation (ref. 14) of the proposed compensation is diagrammed in figure 7. The pilot's task was to manipulate a side-arm controller to maintain the simulated light, fixed-wing jet aircraft in a wings-level attitude in the presence of turbulence. The subjects were experienced helicopter pilots with recent flight time in military reserve or commercial helicopters. Attitude was displayed on an oscilloscope with a 5-in. CRT; no other instruments were used.

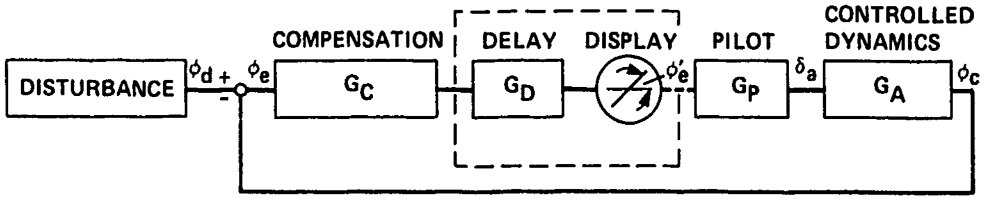

Figure 7.- Diagram of tracking task used in the experiment.

There were three experimental conditions: Baseline, Delayed, and Compensated: they differed only in the processing of the aircraft attitude error signal, ϕ_e (fig. 7). During Baseline trials, attitude error was displayed on the oscilloscope without further processing ($G_C = 1$, $G_D = 1$). During Delayed trials, the attitude error signal was delayed 0.108 sec before being displayed. During Compensated trials, the attitude error signal was filtered in accordance with equation (1) and then delayed 0.108 sec before being displayed. The data from this experiment are unique because the negligible delay of the oscilloscope display made possible acquisition of "no delay," baseline, data to evaluate compensation effectiveness.

The pilot describing-function was computed using the program described by Shirachi and Shirley (ref. 22). The program computes the pilot's average (over the trial) amplitude and phase response at each disturbance frequency. The pilot-aircraft open-loop transfer function was computed from the following:

$$G = G_C G_D G_P G_A \tag{3}$$

where

$$G_C = \begin{cases} 1 & \text{Condition B,D} \\ 0.85\ (0.555S + 1)/(0.372S + 1) & \text{Condition C} \end{cases}$$

$$G_D = \begin{cases} 1 & \text{Condition B} \\ \exp(-0.108S) & \text{Condition C,D} \end{cases}$$

G_p = pilot describing function (measured)

G_A = aircraft transfer function

S = Laplace transform operator

Crossover frequency was estimated by interpolating the open-loop transfer function data. Compensation parameters were based on crossover frequency estimates ($\bar{\omega}_c$ = 1.8 rad/sec) from preliminary Baseline trials. The attitude error signal (ϕ_e fig. 7) was squared and integrated over each trial as a measure, integral-squared (ISE), of pilot performance. Average (over trials) integral-squared error (ISE) is plotted versus experimental condition in figure 8. When averaged over pilots, ISE was 38% larger for the Delayed condition than for the Baseline condition. The average increase in ISE was reduced to 19% for the Compensated condition.

Pilot phase-response summed over the six disturbance frequencies and averaged over trials is plotted versus experimental condition in figure 9. The average (over pilots) decrease in lag (increase in lead) between the Baseline and Delayed condition was 28°. The increase in pilot lead is an indication of an increase in pilot workload, which would bias the results of a simulation by influencing the pilot's rating of the handling qualities of the simulated aircraft. The average increase in lead was reduced to 9° for the Compensated condition. Complete details of the experiment and additional experimental data were reqported in reference 14, which concluded that

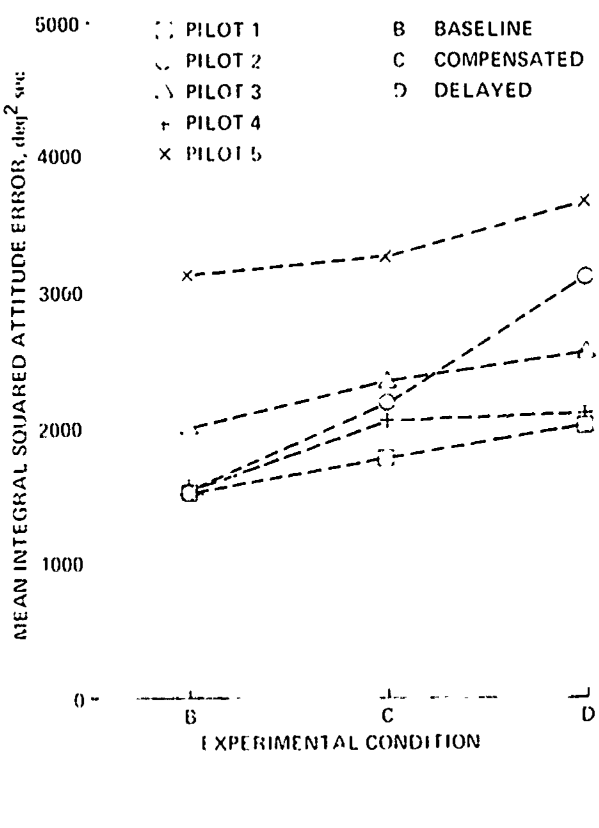

Figure 8.- Mean-integral-squared attitude error as a function of experimental condition.

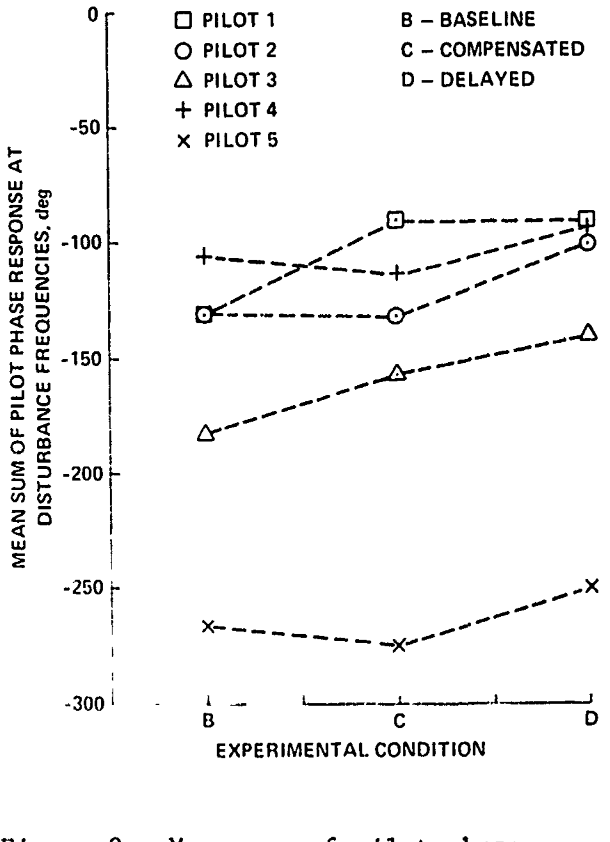

Figure 9.- Mean sum of pilot phase-response at disturbance frequencies as a function of experimental condition.

(1) The compensation was effective. When using the compensated display, measures of pilot performance and workload and pilot-aircraft system measures of stability and responsiveness approached "no-delay" values.

(2) Pilot-to-pilot differences in dynamic response were small enough that compensation, based on average pilot dynamics, improved performance and/or workload measures for all pilots.

CGI Visual Display System: XV-15 Simulation

The CGI system used here (Model F-111, manufactured by Link Division, Singer Corporation) has three major subsystems: a general-purpose computer, special-purpose image-generator hardware, and video electronics. Figure 10 is a timing diagram of a simulation which includes the CGI visual display system.

The aircraft dynamics computer and the CGI system computer are not synchronized. The frame time of the CGI processor is fixed at 33.3 msec. The minimum frame time of the dynamics computer increases with simulation complexity. The dynamics processor samples pilot control inputs, integrates the equations of motion, applies lead compensation (described here) to *selected* variables, and transfers pilot position and attitude and position and attitude rate-or-change information to the CGI system. The CGI computer uses the rate information to extrapolate the position and attitude data to the time corresponding to the beginning of the next frame. An updated image is displayed every 33.3 msec. However, as a result of the CGI system "pipeline" architecture, three frames (100 msec) are required to generate and display the image corresponding to each new pilot position.

A brief evaluation of CGI visual display-delay compensation in the context of a complete six-degree-of-freedom simulation was recently completed. Motion cues were provided by the Ames Research Center Vertical Motion Simulator, a six-degree-of-freedom motion system with ±30 ft of vertical travel.

The aircraft simulated was the XV-15. The XV-15 is a proof-of-concept aircraft which features a rotor system that can be oriented such that it can be flown as a helicopter or as a conventional aircraft (ref. 23). As noted earlier, analysis of the pilot-aircraft system indicates that a given display-delay will be most troublesome when a pilot is attempting precise control of a responsive aircraft that has

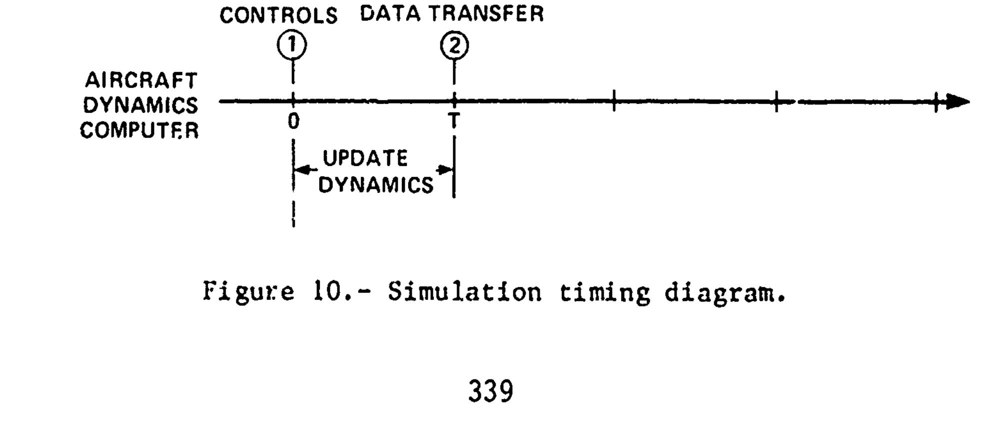

Figure 10.- Simulation timing diagram.

relatively low inherent stability. For the compensation evaluation tests the roll-axis stability and control augmentation system (SCAS) was turned off, mimicking a SCAS system failure. This resulted in an XV-15 configuration with reduced lateral stability, a configuration relatively susceptible to the destabilizing effect of visual-display delay. The lateral control breakout force was set to zero and the lateral control-force gradient was reduced because these control characteristics were more familiar to the commercial helicopter pilots used for the initial tests.

Only the roll-attitude signal was compensated before transfer to the CGI. Compensation filter [eq. (1)] parameters ($T_z = 0.555$, $T_p = 0.384$, $K_D = 0.86$) were selected by the following procedure. In preliminary tests, the roll-axis pilot describing-function ($G_{p\phi}$) was computed from XV-15 roll-axis tracking-task data as described previously. The pilot-aircraft, roll-axis, open-loop transfer function was estimated as the product of $G_{p\phi}$, and a linear approximation of the aircraft roll-axis dynamics. Crossover frequency was estimated by interpolation of the open-loop transfer function data. The filter zero was placed at estimated crossover frequency ($\hat{\omega}_c = 1.8$ rad/sec). The filter time-constant T_p was computed from equation (2) to restore phase margin, and K_D was chosen such that the filter amplitude ratio at $\hat{\omega}_c$ was unity to maintain bandwidth. As noted earlier, the filter gain characteristic distorts the visual display in that frequencies $\ll\omega_c$ are attenuated (~14%) and frequencies $\gg\omega_c$ are amplified (~20%). This relatively small display (roll attitude) distortion was accepted in order to restore system stability and maintain system bandwidth. There was no pilot comment to indicate that gain-distortion effects were noticeable to the pilots. (Note the maximum phase lead of the filter is at ω_m (fig. 5). Therefore, if ω_c is known precisely, some additional reduction in gain distortion is theoretically possible by choosing ω_z and ω_p such that $\omega_m = \sqrt{\omega_z\omega_p} = \omega_c$.)

The piloting task was selected to expose lateral-axis handling-qualities deficiencies. The XV-15 simulation (helicopter configuration, roll-axis SCAS off) was initialized approximately 15 ft above a road. The pilot was briefed to "sidestep briskly to the opposite side of the road and stabilize lined up precisely with the edge of the road," and then to "repeat the task to the opposite side of the road and continue back and forth across the road in this manner." Pilots considered the task to be a good test of lateral handling qualities. Figure 11 illustrates the inner (attitude) and outer (position) lateral-control loops closed by the pilot. The inner loop has the higher bandwidth and is therefore more susceptible to delay-induced instability. Outer-loop precision depends on inner-loop stability.

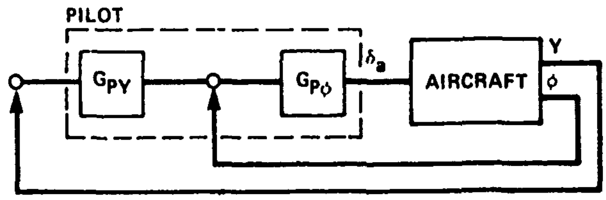

Figure 11.- Loop structure for precision lateral sidestep task: $G_{p\phi}$ and G_{py} are pilot describing functions for roll-attitude control and lateral position control, respectively.

After practicing the task with the visual display both compensated and uncompensated, the pilot made evaluation runs. Figure 12 is a copy of the strip-chart record of the consecutive evaluation runs by an Ames Research Center test pilot who had extensive XV-15 Experience. For the "no-compensation" case, the pilot reported that several cycles of control were required to dampen attitude oscillations after each sidestep across the road and rated the aircraft handling qualities a seven on the Cooper-Harper scale. The compensated case was judged to be more like the XV-15 (SCAS off); the configuration was rated a six on the Cooper-Harper scale. The

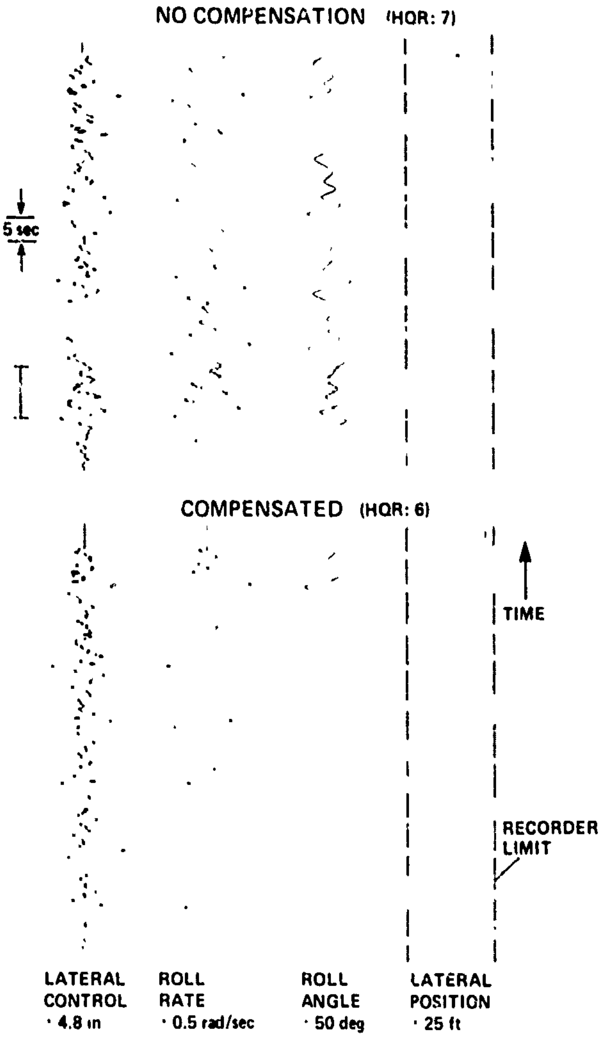

Figure 12.- Compensation evaluation results: XV-15 model, roll SCAS off, precision sidestep maneuver.

strip-chart record confirmed the pilot's report: in the "no-compensation" case, objectionable, lightly-damped oscillations in the lateral control, roll-rate, and roll-angle traces are apparent (e.g., shaded area, fig. 12). (The frequency of the oscillation, as measured from the strip chart, is approximately equal to $\hat{\omega}_c$ (1.8 rad/sec) estimated as described above. It may be possible to simplify the compensation design procedure by estimating ω_c directly from appropriate strip-chart records.)

Another pilot also reported an improvement in handling-qualities rating when performing a similar hover task with the compensated display. These results, though limited in scope and number (by simulator availability), are consistent with the more detailed single-axis data reviewed previously. The XV-15 data illustrate the distortion in aircraft handling-qualities ratings that can result from visual-display delay and the use of *selective* compensation to restore system stability and handling characteristics.

CONCLUDING REMARKS

McRuer and Krendel (ref. 7), and others have shown that pilots performing precision tracking tasks can often be modeled as quasi-linear describing functions. This fact permits analysis of the effects of time-delay in certain man-machine control systems using linear control-system analysis techniques. The analysis indicates that when pilots are performing precision tasks, a reduction of system stability is the immediate effect of additional control system delay. The reduction in system stability influences pilot workload and performance and, therefore, biases aircraft handling-quality ratings. The reduction in system stability is proportional to the trouble index (TI), defined as the ratio of the change in system phase margin (due to delay) to the nominal system phase margin. The TI emphasizes the fact that system characteristics (ω_c, ϕ_m') moderate or exaggerate the importance of a given delay. A selection of data (simulator and flight test) that is consistent with the analysis was reviewed here. It is fortunate that the linearity assumptions required by the analysis are reasonable in many precision tasks where delay is most troublesome.

Simulator visual-display-delay compensation designed to restore system stability while minimizing compensation-filter-gain distortion effects on system responsiveness, tracking accuracy, etc., was evaluated in several studies reviewed here. The compensation was effective; improvement in pilot performance and workload or aircraft HQR were observed. Pilot sensitivity to change in system dynamics is illustrated by the Wood-Hodgkinson envelopes (fig. 6). That data implies that the

compensation design emphasis on visual cue fidelity in the region of crossover frequency is necessary to minimize bias in HQR due to delay or delay compensation. Additional research is required to evaluate compensation effectiveness over a comprehensive range of aircraft dynamics, flight task, and controller nonlinearity.

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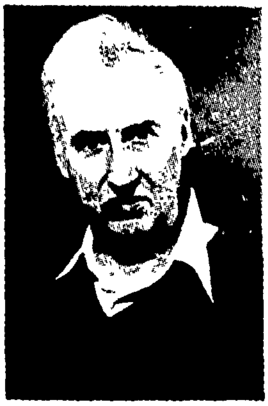
THE FIBER-OPTIC HELMET-MOUNTED DISPLAY



Brian Welch obtained a B.Sc. in Physics at University College London, in 1961. He joined CAE Electronics in 1965 and has worked on several aspects of flight simulation. Most of his efforts, however, have been directed toward visual simulation. He was responsible for the development of high-resolution television equipment for a camera/modelboard visual system in the early 70's. Since then he has been active in the search for high performance display systems and is currently responsible for the Fiber-Optic Helmet Mounted Display Program.

Martin Shenker, in his 35 years at the Farrand Optical Company, has designed many complex optical systems, having had particular experience and success in the design of systems with unusual requirements. His work in Visual Simulation started in 1959 with his design of the first wide field, real exit pupil Infinity Display System for NTEC, located then at Port Washington, N.Y. His involvement in the design of new Visual Simulation Optical Systems has continued to the present time. Mr. Shenker is a Fellow of the Optical Society of America.

THE FIBER-OPTIC HELMET-MOUNTED DISPLAY

ABSTRACT

The feasibility of the Fiber-Optic Helmet-Mounted Display (FOHMD) concept has been demonstrated on a breadboard system installed on a simulator at the Air Force Human Resources Laboratory (AFHRL). Behavioral and engineering evaluation are currently being conducted to determine the optimum design specification for an Engineering Prototype scheduled for completion in late 1984.

This paper describes the significant engineering aspects of the FOHMD together with the exploratory program for improving its performance.

INTRODUCTION

The FOHMD is being developed for the AFHRL by CAE Electronics Ltd. under the Canada/US Defense Development Sharing Agreement. The major subcontractors on the program are Farrand Optical Company Inc. and AO Reichert Scientific Instruments.

The FOHMD approach enables a bright high-resolution full color computer-generated image to be displayed to a pilot over a wide field of view for a relatively low cost. Coherent fiber-optic cables are used to relay images from a number of G.E. light valve projectors to the helmet-mounted optics, allowing a collimated view of the external world to be combined with the direct view of the cockpit instruments and HUD, etc. The head position and attitude are continually being measured and are combined with those of the aircraft to control the computer generated imagery. The field of view seen by each eye is equal to 80 degrees horizontally by 64 degrees vertically. The binocular overlap area is variable but is presently set to 25 degrees giving a total horizontal field of view of 135 degrees. A high-resolution (1.5 arc minutes per pixel) inset field is centered within this field of view in the overlap region.

Two channels of computer-generated imagery are used to drive the background field and the inset field for each eye. If stereoscopic imagery is not a major requirement, the inset field for both eyes can be driven by a common channel. A full description of the FOHMD has been given by Capt. Hanson (Ref. 1). Figure 1 shows the complete system and Figure 2 is a schematic of the optical components.

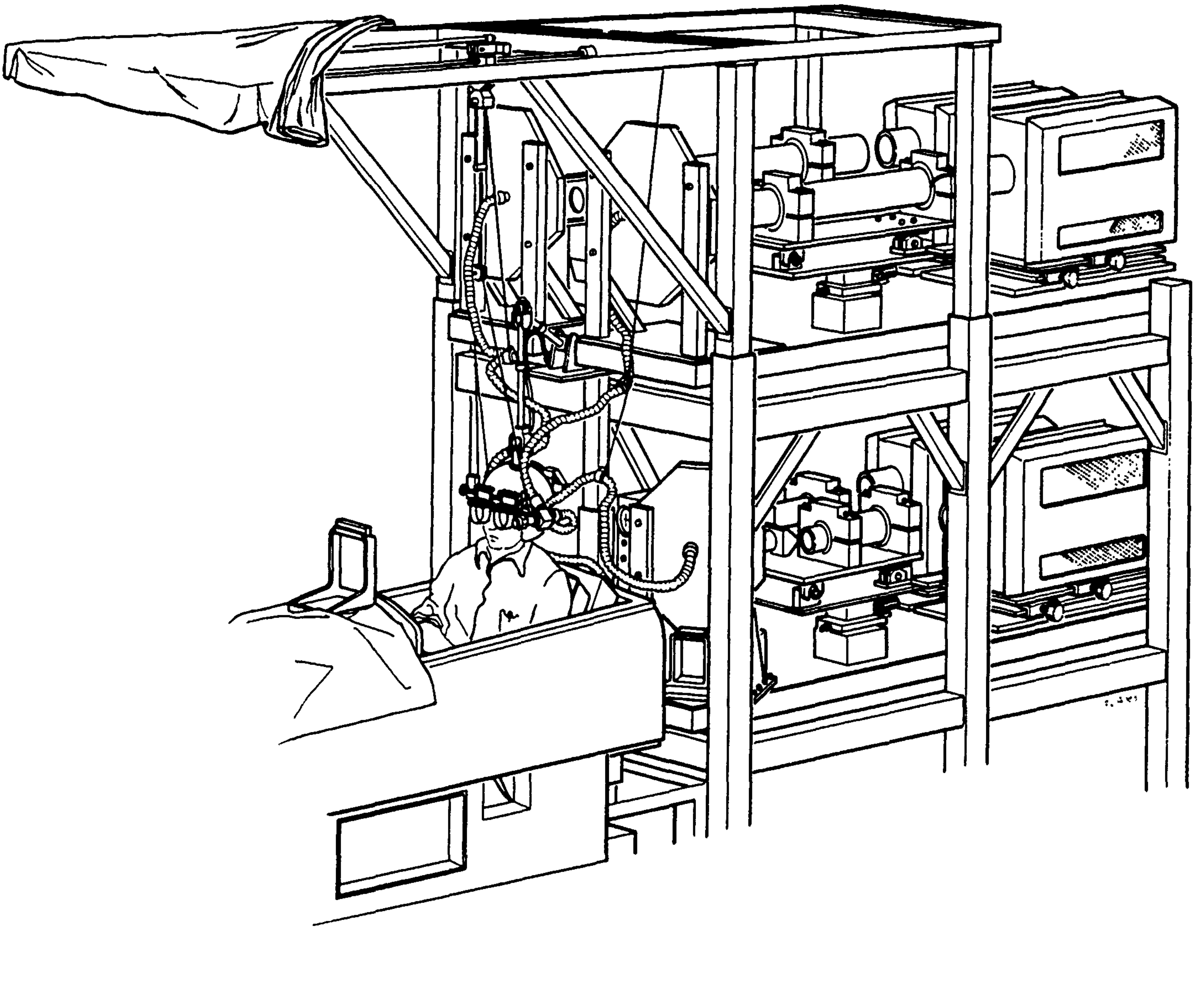


Figure 1 Physical Layout of FOHMD Components

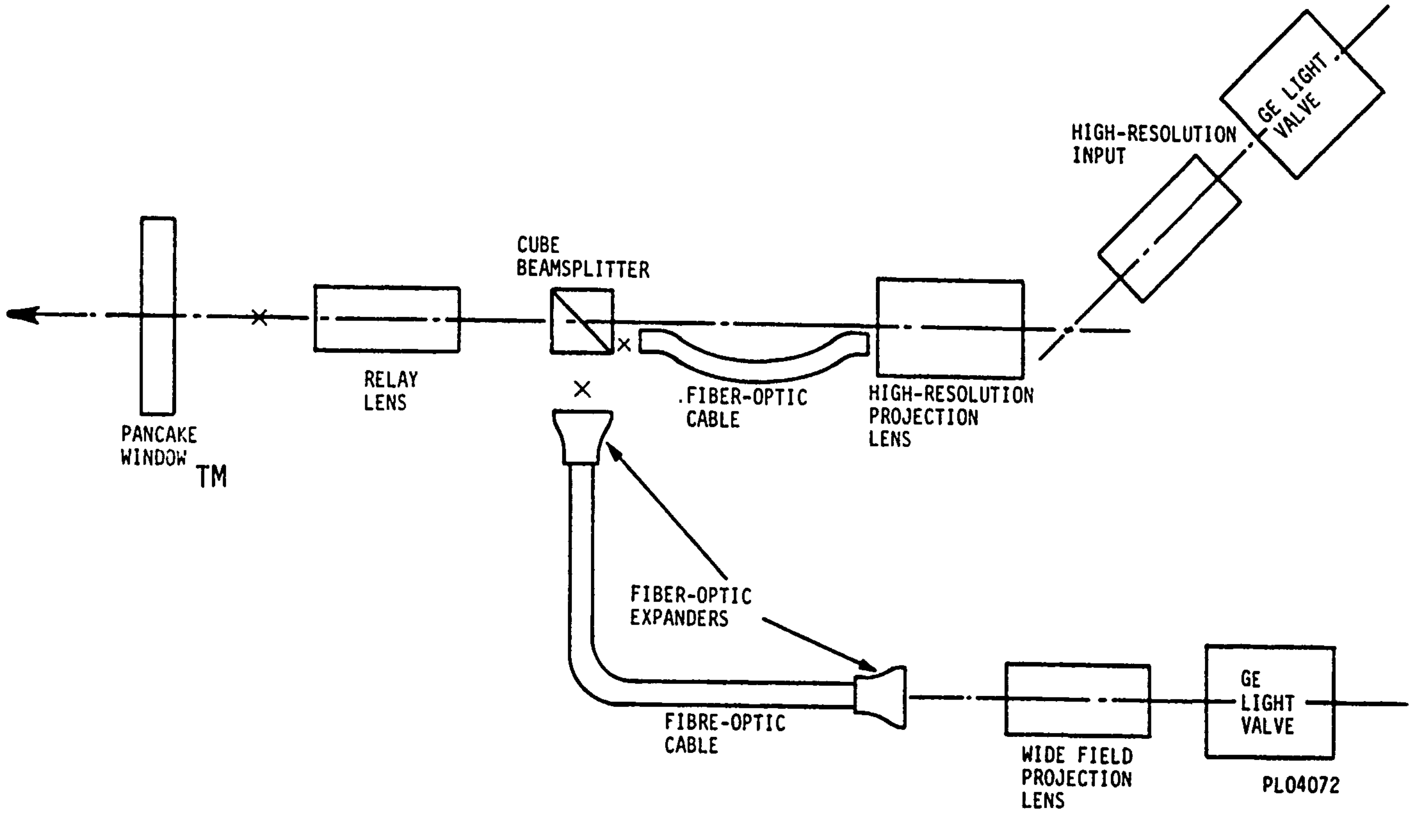


Figure 2 Schematic of Optical System for Each Eye

CURRENT STATUS

The FOHMD program started on June 1st, 1981. The breadboard helmet display was delivered to AFHRL in January 1983 and served as a test bed allowing many aspects of this approach to be investigated and to a large extent solved before the FOHMD was connected to a flight simulator. Full integration with a pair of Singer DIG's and a generic fighter simulator did not occur until October 1983. This breadboard system is being used in both engineering and psycho-physical experiments to determine acceptable parameters for an engineering prototype FOHMD scheduled for delivery at the end of 1984.

It is expected that the psycho-physical experiments will also provide considerable insight regarding the ultimate potential of the FOHMD as a training device. The following paragraphs describe some of the more interesting design problems encountered during the development of the breadboard together with certain improvements which will be incorporated into the Engineering Prototype FOHMD.

FIBER-OPTIC CABLES

The resolution goal for the HMD was 2 to 3 arc minutes per line pair. Such high resolution was only required in that part of the field of view where foveal vision would normally be used. The area outside this region could be allowed to progressively degrade without affecting the observer's perception of the displayed image. Although a number of approaches were suggested at the beginning of the project for obtaining the required resolution using one fiber-optic cable for each eye, it was decided that the lowest-risk approach for the breadboard design would be two cables for each eye. One cable would be used to provide relatively low-resolution imagery outside of the central region and the other would provide high-resolution imagery in the center of the overall field of view. This approach allowed conventional fiber-optic cables to be used and, at the same time, allowed exploratory work on cables having more desirable characteristics to proceed as a parallel development.

Image Enhancement in Fiber-Optic Cables

The quality of an image transmitted through a fiber-optic bundle can be seriously degraded by the structure of the fiber bundle. The image falling on a single fiber is averaged in both color and luminance to form a single pixel at the output image. The spacing of the fibers therefore determines the limiting resolution and the MTF of the cable. As this is a quantizing process, aliasing effects will also occur. A significant degradation also occurs due to the fixed-pattern noise produced by the multifiber structure. The current manufacturing process in the USA for large coherent bundles first produces a 5 x 5 array of single fibers which is then wound on a drum to form continuous ribbons of the desired width. These ribbons are then stacked together to form a rectangular block of the required size which is impregnated with epoxy and cut to obtain a single coherent bundle. The array or multifiber structure is very visible. A further small degradation is due to the slight noncoherence caused by minor variations in the spacing of the multifibers and the removal of a portion of the fibers during the cutting and polishing procedure.

The effect on image quality of these manufacturing characteristics can be reduced considerably by the use of either color or dynamic multiplexing. Both techniques, although quite different in implementation, cause each image element to be transmitted by many individual fibers. Upon recombination at the output end of the cable, the structure of the fibers is suppressed and the image quality is considerably enhanced. Both techniques were tried and are described in the following paragraphs.

Color Multiplexing (Ref. 2)

This approach uses a prism at the input end of the cable to spread each pixel of the image into a linear spectrum covering several multifibers. An identical prism is used at the output end to correct the color dispersion. If the spectral dispersion is large enough, broken multifibers appear as faintly colored streaks. If the dispersion is equivalent to only 2 or 3 multifibers, this becomes a fairly brightly colored defect. Tests with a G.E. light valve showed

that a dispersion of 0.5 mm between blue and red was sufficient to reduce the effect of a broken multifiber to negligible proportions. The color multiplexing technique was actually used in the breadboard design but other optical design considerations prevented more than 0.2 mm of dispersion from being used. Although the overall image quality in the 25-degree inset is quite high, the fixed pattern noise and broken fibers are still visible. The effect of this residual fiber structure will be evaluated on the breadboard system. It now seems possible to use a greater amount of spectral dispersion and, if the engineering prototype retains this image enhancement technique, the dispersion will be equivalent to at least ten multifibers.

The effect of color multiplexing on resolution can best be understood by considering the image produced by a single point source of light as shown in Figure 3. The image is spread over many fibers by the prism at the input end of the bundle. The light emitted by each fiber at the output end of the bundle is distributed evenly across the fiber in both amplitude and color. The correcting prism produces an image having a width at 50% of peak luminance equal to the diameter of the fiber cores (d). The minimum separable acuity is therefore approximately equal to d. A mathematical calculation of MTF is somewhat complex, however, measured MTF curves of a standard cable are shown in Figure 4.

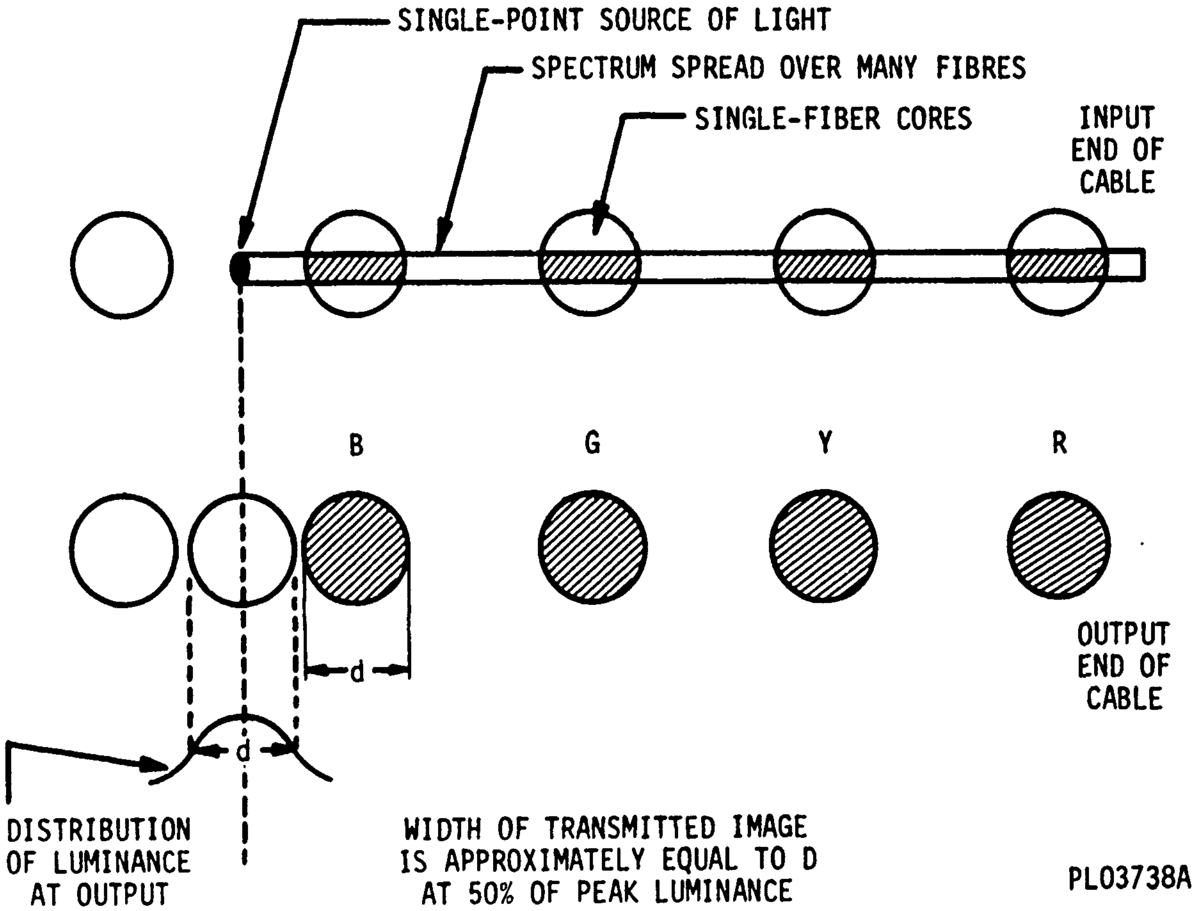
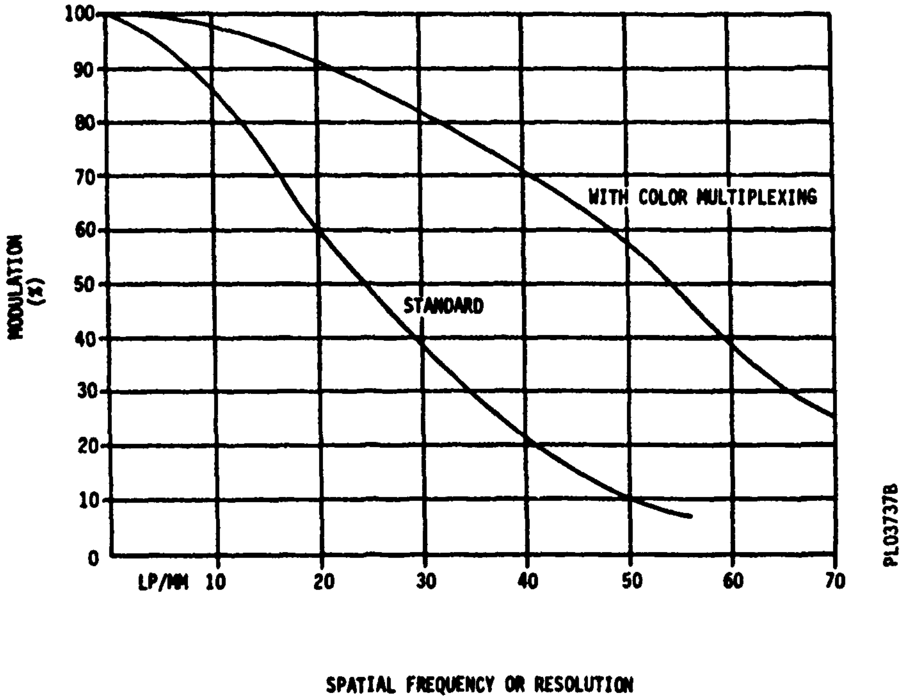


Figure 3 Effect of Color Multiplexing on Spread Function of Point Light Source



NOTE: STANDARD FIBER-OPTIC CABLE HAS AN 8-MM BY 10-MM IMAGE FORMAT, 10-MM FIBERS AND IS 4-FEET LONG.

Figure 4 Standard Fiber-Optic Cable MTF

Dynamic Multiplexing

The alternative approach for image enhancement is dynamic multiplexing. The input image is physically scanned across several multifibers in either a circular or random manner. When the output image is scanned in a synchronous fashion, the fiber structure is eliminated and the resolution is improved considerably. The theory is described in some detail by Kapany (Ref. 3). An attempt was made to incorporate this technique in the breadboard design. Several difficulties, however, made this impractical and the color multiplexing approach was adopted. Nevertheless, it was generally accepted that the image quality was superior using the dynamic multiplexing technique and work is continuing to find a way of incorporating this technique into future designs.

High-Resolution Cables

The image enhancement techniques described above offer a method for making much higher resolution cables with the same cross-sectional area as standard cables. The resolution of cables using either technique is governed by the diameter of the fiber core. If a cable is made using fibers with the standard 10-micron cladding diameter, but 3-micron cores instead of the usual 8 microns, an increase in limiting resolution of 8/3, i.e., 2.7, can be expected. A decrease in transmission of 2.7^2, i.e., about 7.3, can also be expected.

A 13-mm cable employing this technique is being made by AO Reichert Scientific Instruments who have supplied all the fiber-optic components for this program. It will provide resolution equivalent to 4000 pixels across the entire 80-degree field allowing only one cable to be used for each eye.

An alternative approach for high-resolution bundles using the leaching process developed many years ago by AO Reichert is also being explored. It consists of drawing a solid hexagonal fiber-optic rod, 2 mm across, containing about 20,000 individual fibers. These rods are similar to those used in the manufacture of fiber-optic faceplates except for an extra layer of acid soluble glass around each fiber. If the ends of the rod are encased in wax and the whole rod immersed in acid for a certain length of time, the outer layer of glass is leached away leaving a flexible bundle with perfect coherence between each end. Such bundles are currently being used by the medical profession in endoscopes, etc. Combining several of these bundles could provide a large format cable with no multifiber structure and may allow the image format size to be specified independently from the diameter of the bundle. If before the leaching process takes place, the 2-mm rod is drawn one more time except for the two ends, the resulting fiber bundle after leaching can be described as a flexible cable with built-in expanders at each end. Combining these bundles into a larger bundle will produce a cable (shown in Figure 5) in which the diameter of the flexible part of the bundle is considerably less than that of the two ends and has an inherent transmission similar to that of a conventional fiber bundle.

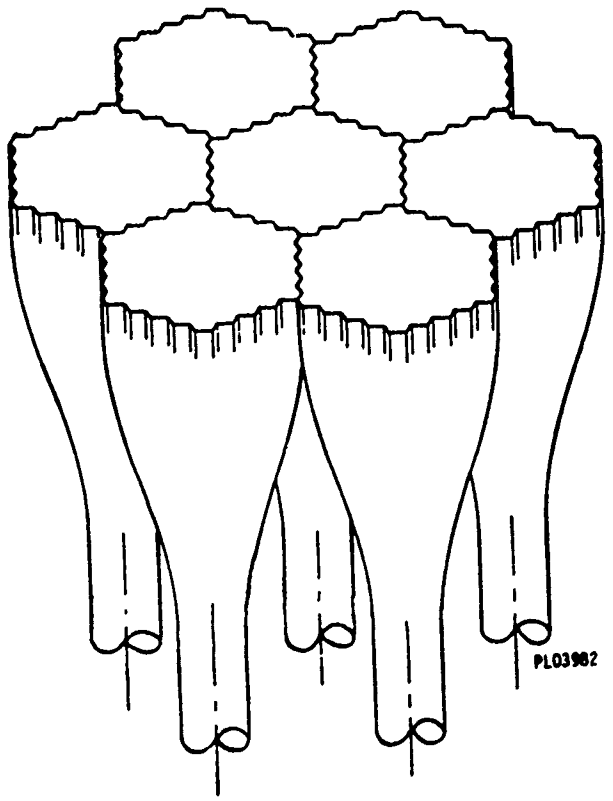


Figure 5 Leached Bundle Array with Built-In Expanders

OPTICAL DESIGN

The total Visual Display System of the FOHMD, including the image generation system, may be considered to be the analog of a distortion-free one-power "Constant Deviation" Telescope.

The unique characteristic of such a "Constant Deviation" Telescope is that when the total telescope is rotated to a different viewing position, objects in the field remain stationary.

The makeup of the one-power telescopes in the FOHMD may be considered schematically as follows:

An "Entrance Pupil" defining a perspective point and a direction in space are defined for the CGI System.

The generated picture is formed on the oil film of the Light Valve Projector.

This picture is distortion free, i.e., F tan θ mapping*.

The background picture is relayed, scaled, distortion modified and imaged on the input surface of the background fiber optics rope. This rope is actually made up of three fiber optics components with the output image matching the input image. The overall distortion generated at this image is required to match the mapping of the display system.

Working backward from the eye the display system is optically in the form of an erecting eyepiece as shown in Figure 6. The overall focal length of the erecting eyepiece is equal to the product of the focal length of the eyepiece times the magnification of the relay system.

In the breadboard FOHMD system this overall focal length is 21.5 mm with F θ mapping. Thus the relay system from the light valve to the fiber optics input transforms F tan θ mapping to F θ mapping. This has been achieved so that the overall background system is completely distortion free. This emphasis on distortion correction is required because the two 80-degree displays feeding the eyes of the observer have axes that differ by as much as 55 degrees from each other. Thus complete distortion correction is a must if images in the overlap region are to be fused.

The high-resolution input follows a somewhat different path to the eye as an inset portion of the 80-degree field of the background.

*The word mapping in simulator parlance refers to the transformation from angular space to chordal heights on a focal surface. It thus combines both scale (EFL) and distortion.

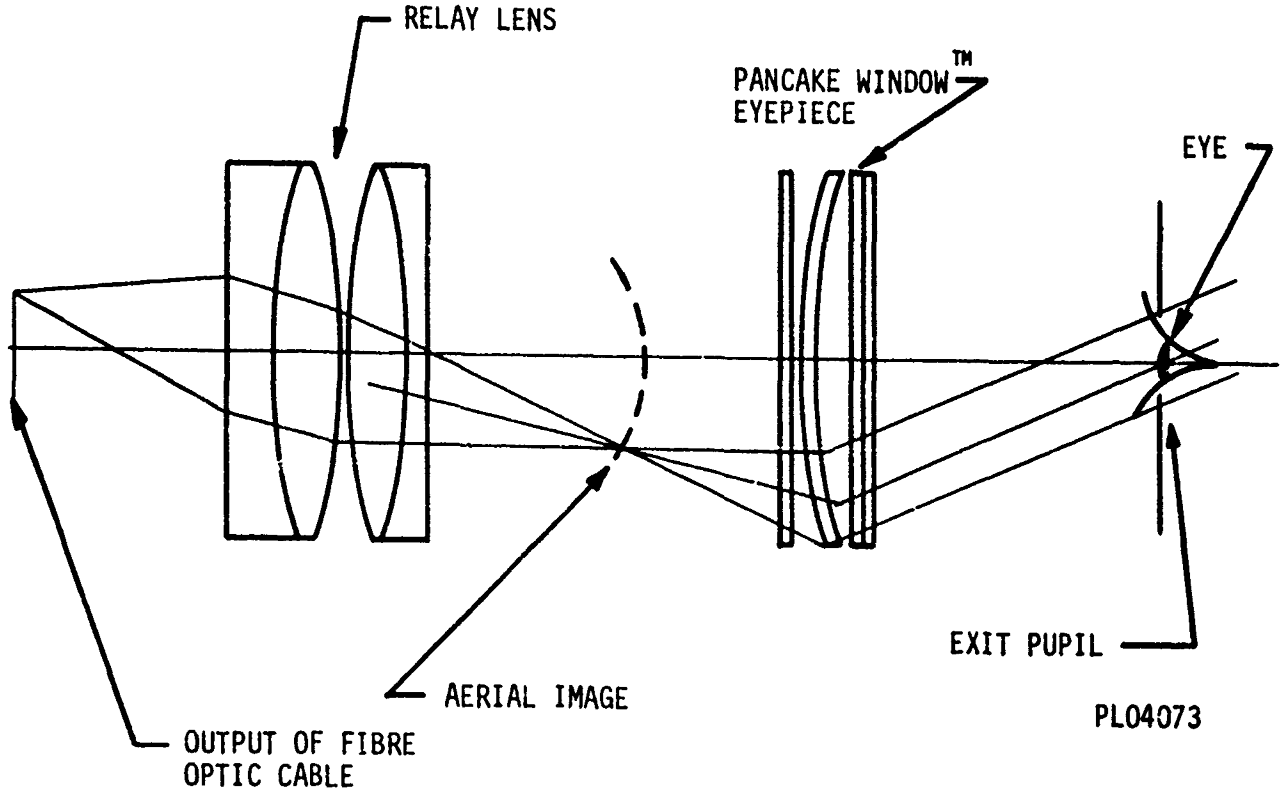


Figure 6 Erecting Eyepiece

In the breadboard system an optical system called the High-Resolution Projection Lens System that has exactly the same 80-degree field of view and mapping as the display system is used. A separate fiber optics rope transfers a portion of the 80-degree image formed by this projection lens to the corresponding portion of the display.

Projecting into the High-Resolution Projection Lens System is the high-resolution input. The axis of this input is defined as a direction in space different from that defined for the background. Thus the entrance pupil for the CGI System is defined at the same point but in a different direction than that defined for the background. The image in the high-resolution picture is F tan θ with the angles measured relative to this new axis. The optical system that works with this High-Resolution Light Valve Projector input collimates this output with an angular coverage exactly matching the input angles computed for the CGI.

Thus we might say that the high-resolution input is generated from CGI to the eye by having a narrow angle one-power constant deviation telescope feeding a one-power wide angle constant deviation telescope. In the breadboard system the angular position of the high-resolution insert relative to the axis of its corresponding wide angle display is fixed but changeable, i.e., if the position is to be changed, the high-resolution fiber optics must be moved to provide an image in a different area of the background.

In the intended prototype system wherein one fiber-optic rope will transfer the images to the display, the image will be movable in a simpler manner. In the eventual system with eye tracking this same system will provide the eye tracked high-resolution insert by providing scanning between the high-resolution input telescope and the high-resolution projection lens.

The hardware of the display system itself is worthy of further mention.

As previously stated, the individual displays are in the form of erecting eyepieces. In the FOHMD they have an EFL of 21.5 mm with an exit pupil = 15 mm in diameter.

Thus they may be described as .35 NA 12X microscopes having fields of view of 80 degrees. The systems have extremely fine aberrational correction so that it is quite practicable to turn out each of the axes by as much as 27-1/2 degrees so that the total field of view can be as much as 135 degrees wide as shown in Figure 7. It should be noted that using these systems in this manner requires an excellent off-axis correction in that the edge of each field is used as the center of the field of the two-eyed display.

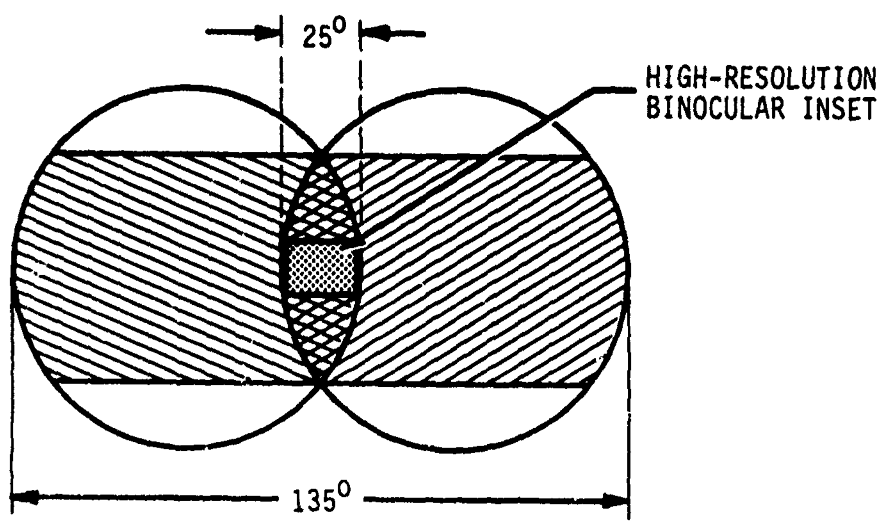


Figure 7 FOHMD Field of View

Head Tracker

A mechanical head tracker was chosen for the breadboard FOHMD for its simplicity, well defined accuracy and speed of response. Any uncertainties in the performance of the head tracker, particularly in its dynamic performance, would have caused difficulties in the evaluation of the imagery. The resolution of the mechanical tracker was 6 arc minutes and a new position was calculated every 17 milliseconds.

Several types of noncontact head trackers were investigated before deciding to build a system based on a technique developed by the National Research Council in Ottawa (NRC) (Ref. 4). The NRC approach used a television camera to view a set of discrete points on an object whose orientation could then be determined by measurement of the position of each point on the television image. The inherent accuracy and response time have been improved considerably by using a Hamamatsu position sensor rather than a television camera. The breadboard system is currently being developed by Concordia University in Montreal and is scheduled for integration with the breadboard FOHMD in May of 1984.

Two sensors viewing the same LED pattern are required to uniquely determine the helmet position in six degrees of freedom. The image on the sensitive area of the detector is a two-dimensional perspective projection of an LED moving in three-dimensional space. Consequently, the three-dimensional position of the LED cannot be uniquely determined from its image coordinates. At best, only the direction of the vector between the LED and the sensor can be determined. If the target LED is viewed from two locations, a triangulation scheme can be used to compute the LED's position in three dimensions. Three LED's and two sensors allow the helmet position to be uniquely determined in all six degrees of freedom. The addition of more LED's results in an overdetermined system of equations which can increase the accuracy of the measurement through the application of least-squares analysis.

Figure 8 shows the physical relationship between the sensors and the FOHMD.

Positional data will be obtained at a 120 Hz rate and the resolution should approach 2 arc minutes.

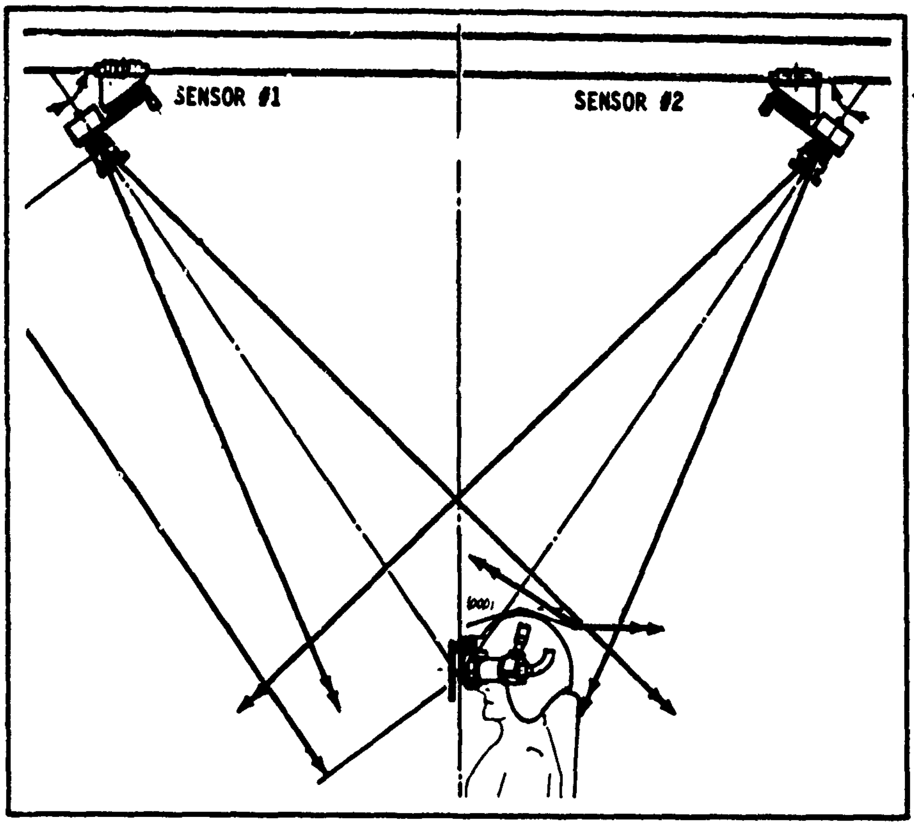


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Figure 8 Physical Relationship Between Sensors and Helmet

Image Stability

One of the major concerns in the early stages of this project was whether or not a stable image could be obtained on a helmet-mounted display.

All computer-generated image systems have an inherent transport delay due to the amount of digital computation required for each displayed image. Consequently, during a head rotation the displayed image will correspond to the head position existing at an earlier point in time. If no corrective action is taken the image is displaced in the direction of head motion and only returns to the correct position in space when the head motion returns to zero.

The original concept for stabilizing the image used a mechanical device to steer the image in the opposite direction to head motion. A push-pull arrangement of linear motors moved the input of the fiber-optic bundle in the direction corresponding to yaw and pitch. Movements equivalent to ±6 degrees could be obtained with a response time of approximately 10 ms. Figure 9 shows a hypothetical head movement with corresponding image generator motion. The difference between these two motions is the required displayed image motion for obtaining a stable image.

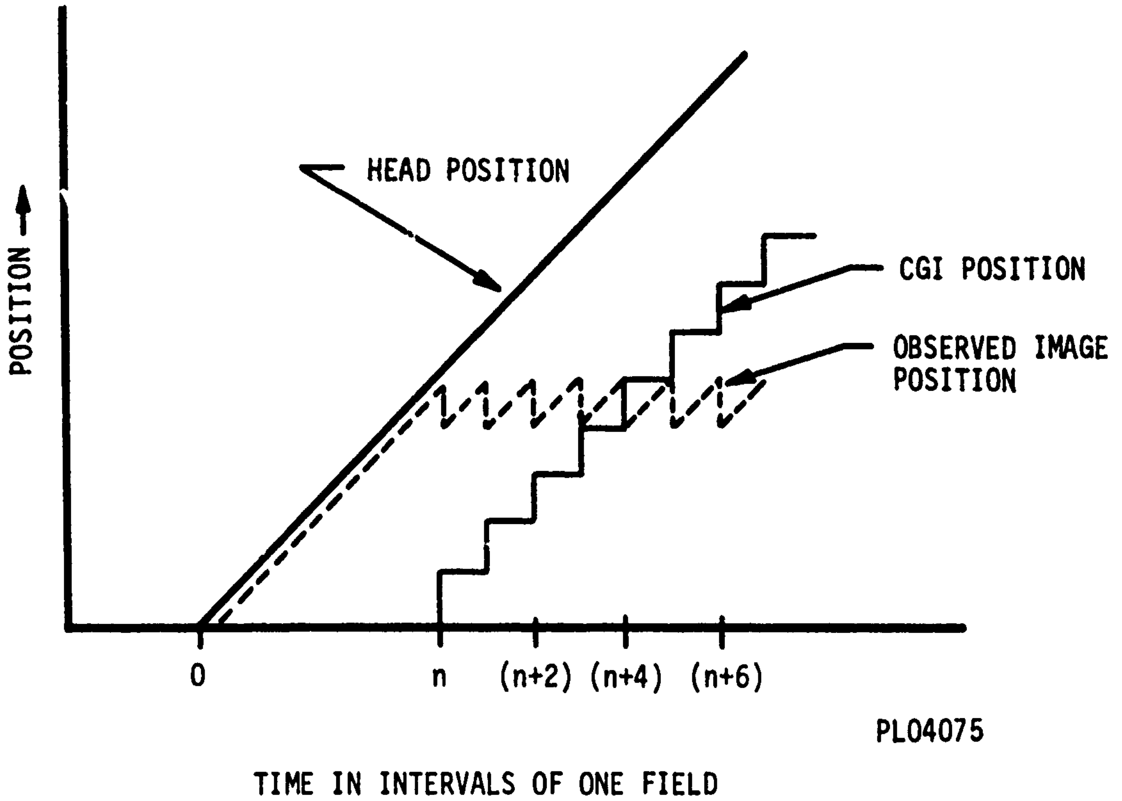

Figure 9 Effect of CGI Transport Delay on Image Stability

An electrical signal corresponding to this motion was derived from the head tracking system as shown in Figure 10. This technique proved to be extremely effective when the total transport delay of head tracker and DIG system was no greater than 65 ms. The maximum excursion of the optical steering device seemed to be insufficient to accommodate longer delays. The main disadvantage of this approach is the need for a slightly larger fiber-optic cable to prevent loss of imagery during head movements. A production version of this approach would probably utilize scanning mirrors and an image rotator to obtain the desired correction in all three rotational axis.

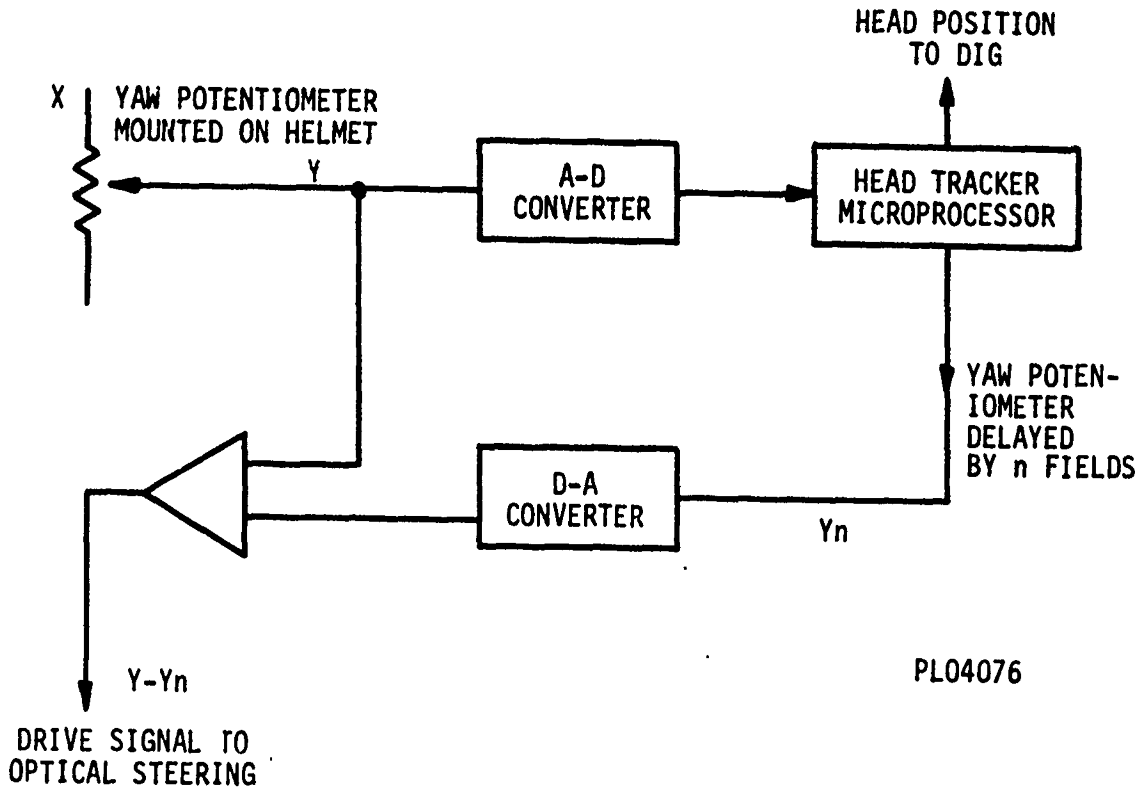

Figure 10 Derivation of Optical Steering Control Signal. Identical Networks Used for Pitch and Yaw.

An alternative scheme using a prediction algorithm based on measured head acceleration to control the calculated image position was also implemented. A full description of this technique is given by List in Ref. 5. Initial evaluation has indicated that prediction of head position is just as effective as the optical steering technique. Figure 11 shows a typical head movement and the resulting image movement (E) with no correction. It can be seen that the image movement continues to increase until the head starts to decelerate. When the prediction algorithm is used the image movement decreases immediately after the transport delay. It is interesting to note that the amount of image movement seems to be proportional to the square of the transport delay. AFHRL and Singer Link personnel have expended considerable effort to reduce the overall transport delay to about 65 ms. It is of course impossible to reduce image movement to zero with this technique, but a modest amount of optical steering combined with a prediction algorithm should be able to reduce image instability to an imperceptible level.

Further experiments will be conducted to determine whether the prediction method is sufficient in itself or whether a combination of prediction and optical steering is necessary.

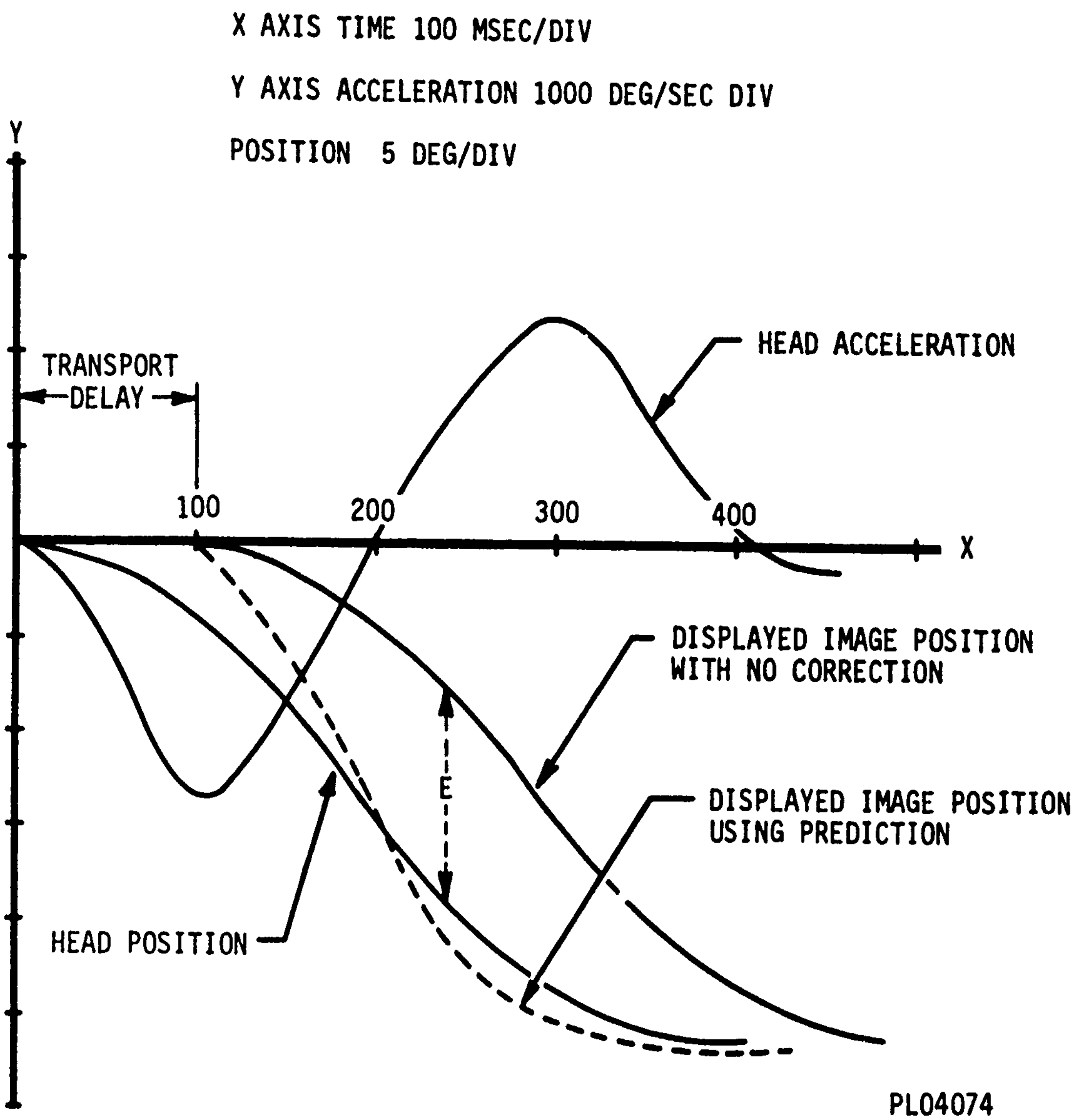

Figure 11 Typical Head Movement Showing Displayed Image Position With and Without Prediction (From List Dec. 1983)

FUTURE PLANS

Apart from the obvious efforts in the areas of lightweight materials and smaller fiber-optic cables, the remainder of the program will largely be directed toward an eye-slaved inset. Sufficient experimental work has been done by both industry and government research facilities to convince most potential simulator users of the need and feasibility of eye-slaved displays.

The optical design of the engineering prototype currently being built will allow the high resolution inset to be rapidly scanned in response to eye movements. Current plans also call for the development of an eye tracker to be integrated with the helmet optics and a series of experiments to determine the essential characteristics of a computer image generator used in an eye-slaved mode.

A related effort will investigate the possibility of using an eye-slaved variable acuity function (Ref. 6) in the image generator to replace the fixed resolution inset. If successful, the CGI requirements would be reduced to a total of two channels. A significant effort will also be directed toward increasing the size of the exit pupil from the present 15 mm to 25 mm. Such an increase would eliminate several adjustments and reduce overall weight.

A considerable number of psycho-physical experiments have also been planned including transfer of training experiments with both the fixed and eye-slaved versions of the FOHMD. It is believed that the current program will lead to the development of a visual system which will enable a high proportion, if not all, air-to-air and air-to-ground missions to be trained and practiced in relatively low-cost simulators.

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AD-P004 331

BINOCULAR OVERLAP IN A FIBER OPTIC HELMET MOUNTED DISPLAY

No Photo Available

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BINOCULAR OVERLAP IN A FIBER OPTIC HELMET MOUNTED DISPLAY

ABSTRACT

Target detection, motion detection, and flight performance were compared under conditions of 25° and 45° binocular overlap using only the low resolution background channels of a Fiber Optic Helmet Mounted Display (FOHMD). In experiments 1 and 2, eight experienced fighter pilots viewed aircraft targets which either approached ownship or moved vertically in the field of view, respectively, at various angles of off axis eccentricity. As an additional task, pilots flew the system as an air combat simulator and were required to track, engage, and destroy an airborne target. The results indicated target and motion detection with binocularly displayed targets were superior to that of monocularly displayed targets. There was no significant difference in target detection or motion detection between the two overlap conditions, per se, nor between left and right fields of view. In both overlap conditions, performance was degraded within 5° of the lateral edges of the field of view, and suppression was evident in contralateral fields in the areas of optical frame overlap. However, the latter effects were combined nearer the central viewing area for the 25° overlap condition. No significant differences were noted in the supplementary air combat task as a function of overlap, but structured debriefing data indicated loss of target imagery was less of a problem with the larger overlap. It was concluded that greater than 25° binocular overlap should be utilized in follow-on systems.

INTRODUCTION

Although wide field of view simulators have been produced for R&D purposes, they remain prohibitively expensive for widespread distribution. Moreover, demonstrated approaches, such as the dodecahedron cathode ray tube mosaic or the dual channel dome projection system, have, to date, proven deficient relative to the combination of field of view, modulation transfer function, and short throughput delay required for advanced air-to-air and air-to-ground tactical simulation training. The fiber optic helmet mounted display (FOHMD) was conceived as an innovative solution to existing display deficiencies. An initial breadboard version of the FOHMD was fabricated to permit preliminary experimentation which would help define design requirements for a more refined, follow-on prototype. Details of the breadboard configuration and design may be found elsewhere in these proceedings (Welch and Shenker, The Fiber Optic Helmet Mounted Display), and also in Hanson (1983). The breadboard system was designed as a research vehicle capable of a wide range of adjustment and modification for experimental purposes. The prototype system, yet to be fabricated, will be more limited in its flexibility for modification, but will incorporate breadboard research results intended to better optimize that system for actual flight simulator training utilization. The study described herein is the first in a series of breadboard experiments to achieve that goal.

The optical design of the FOHMD permits limited variation in the degree of binocular overlap. Ideally, a fixed level of overlap would be specified for the prototype system in order to streamline the optical frame and to minimize weight. The available limits for overlap are determined by the relative trade-offs in field of view at the temporal and nasal edges of the optical eye pieces. Increases in the level of overlap are made at the expense of total lateral field of view. Decreases below about 30° overlap are made at the expense of available imagery at the top and bottom of the central viewing area, as the circular eye pieces increasingly separate at their nasal intersection.

In addition to the design ramifications of level of overlap, a concomitant research issue concerns the psychophysical effects of limited binocular overlap on visual performance. Depending on individual physiogamy, binocular overlap in normal vision can be as large as 120° (Fogel, 1963, p. 69). The visual effects of presenting the observer with less than half the normally available overlap is therefore of obvious concern. Research has suggested the existence of specific binocularly tuned mechanisms which are sensitive to the relative velocities of left and right retinal images of an object as a cue to direction of motion in depth, a process which apparently operates well beyond the normally stated limits of stereopsis (Regan, Beverley, and Cynader, 1979; Regan and Beverley, 1979). It would be clearly desirable for the FOHMD to employ a level of overlap sufficient to accommodate any such process especially as it may apply to air-to-air visual descrimination tasks. Limited simulator research has been accomplished on the effects of reduced overlap on air combat performance (Warner, 1981). That research found no significant performance effect on bomb scores or head movement as overlap was reduced from full to 20°. However, the experiment was not conducted in the specific context of a helmet mounted display, nor did it apply to air-to-air visual performance.

In the present study, the effects of two conditions of binocular field overlap, 25° versus 45°, were compared with respect to their effects on aircraft target detection, motion detection, and a simplified air combat task.

METHOD

A. Subjects

Eight experienced F-5 fighter pilots volunteered to participate in the study. Pilots' ages ranged from 27 to 44 years (mean 33) and flying experience ranged from 1,200 to 4,300 hours (mean 2,069). Measured interpupillary distances ranged from 58 to 75mm (mean 63) and eyeball to lens clearance with standard air force eyeglass frames was stable at 15mm. All the pilots had visual acuity of Snellen 20/20 or better. Seven of the eight subjects were right eye dominant.

B. Apparatus

The breadboard version of the FOHMD, as described by Hanson (1983) and by Welch earlier in these proceedings, was the primary equipment in the present study. Included in the system is a T-38 trainer cockpit programmed with F-16 flight dynamics and equipped with a simple Head-Up-Display (HUD). While the FOHMD is normally operated with four display channels (one background and one high resolution per eye), in the present study, only the two background channels were used. A 30 Hz system update rate was utilized. A Singer Digital Image Generation System provided imagery of an aircraft target over a flat earth scene comprised of rectangular patches of varying colors. Automated control of stimulus conditions, flight control, and performance measurement was provided by a Gould SEL 32/55 computer system. A mechanical position sensor, interfaced with an Intel 8086 computer, provided head tracking.

C. Procedures

1) Target Detection Task

In this task, own aircraft was stationary and the head tracking system was disabled. While pilots were free to move their heads, angular orientation of the flat earth scene remained static. The target was a white body silhouette of a MIG 21 aircraft which closed at a rate of 210 knots from .8 nautical miles (NM) to within 100 feet of own aircraft.

In the 25° overlap condition, targets appeared in 26 locations (Figure 1A). Four of these targets were in the overlap area and two at the edges of the overlap area. The latter six targets were presented three times: left field monocularly, right field monocularly and binocularly. The total number of target presentation trials was thirty-eight. Total field of view was 135°. In the 45° overlap condition, targets appeared in 22 locations, with the 10 in the overlap region presented left field, right field, and binocularly, for a total of 42 presentations. Total field of view was 115°. In both conditions, a green fixation cross appeared within 9° visual angle of a target prior to a trial, disappearing as soon as the trial commenced.

The subject's task was to locate the fixation cross and press the nosewheel steering button on the control stick to indicate ready. At this signal, the fixation cross would disappear and the target would commence closing within 2.5 seconds. Subjects were instructed to press the gun trigger on the control stick immediately upon sighting the target. Responses were registered at the first detent of trigger depression. Subsequently, a new fixation cross would appear and the sequence would be repeated. Target presentation order was random without replacement in both conditions. Each trial sequence was

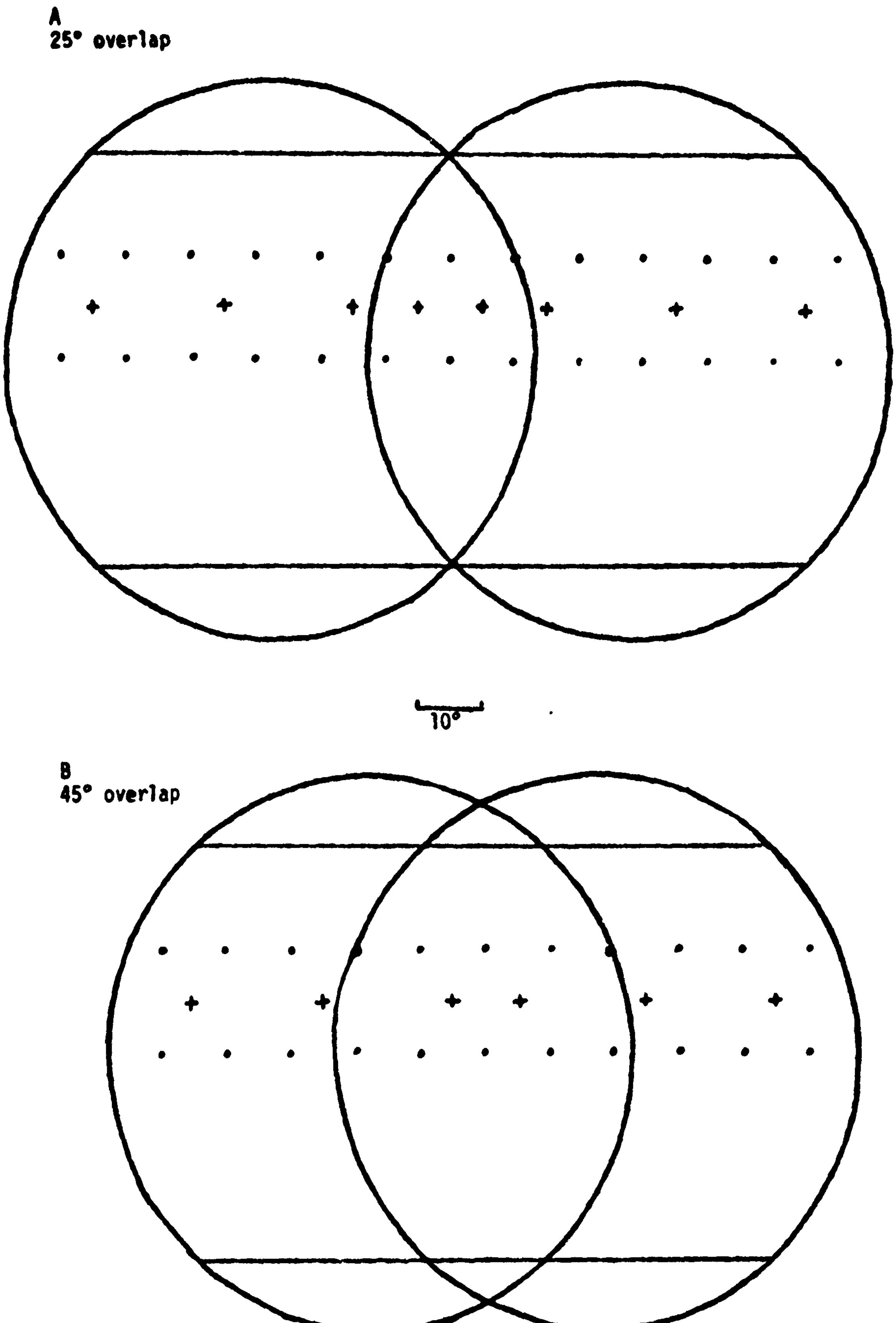

FIGURE 1. Positions for targets and fixation crosses in the two overlap conditions.

about 12 minutes in duration. The index of performance was size of the target in minutes of arc at detection.

2) Motion Detection Task

As in the target detection task, own aircraft was stationary and the head tracking system was disabled. In both 25^{0} and 45^{0} conditions, the target locations from the first task were repeated. As in the first task, a fixation cross was displayed within 9^{0} of a target location prior to the commencement of each trial. To ensure that all targets were equally discriminable, for each subject the size of target at detection in Task 1 was stored for each location and used as the size for motion detection at that location for Task 2.

The subject's task was to locate the fixation cross and press the nosewheel steering button for ready as in Task 1, then press the trigger to confirm sighting the target. Within 2.5 seconds, the target would then move up or down at an acceleration of $1/sec^2$. Upon detecting target motion, pilots were instructed to trim in the direction of target motion with the thumb activated trim button on the control stick. A new target then followed as in Task 1. Target presentation order was random without replacement. A full sequence of trials required about six minutes. The index of performance utilized was latency for motion detection in tenths of seconds.

3) Target Tracking/Air Combat

In this task, pilots flew the system as an air combat simulator. Head position sensing was utilized to provide dynamic scene orientation, which remained appropriate to own aircraft orientation regardless of pilot's head position. Targets were programmed to fly straight and level at 360 knots, heading north away from ownship, at an altitude of either 2,000, 3,000 or 4,000 feet. Targets were initialized at a range of .3 NM (1,800 feet) with an offset from own aircraft's nose of 0^{0}, $+30^{0}$ or $+60^{0}$, for a total of 15 target positions in all. Own aircraft was initialized straight and level at 360 knots, heading north and at an altitude of 3,000 feet. Prior to each trial, a green fixation cross was displayed at the target location.

The subject's task was to locate the fixation cross and press the nosewheel steering button when ready, at which time the cross would disappear and the system would come off freeze. Pilots were instructed to close the target and shoot it down with a gun set to fire at 6,000 rounds per minute with a "laser" trajectory. Ammunition was unlimited. A simple HUD with reticule was provided for aiming. Head position sensing was calibrated relative to own aircraft prior to the commencement of the trial sequence. A trial would end if one round hit the target, or after two minutes had passed from commencement. Duration of a full run averaged about 15 minutes. The

indices of performance were: kill rate, time to gun fire, time to destroy the target and number of rounds fired. Order of target presentation was random without replacement.

4) Order of Conditions

Each pilot completed all three tasks in one session in the 25° or 45° overlap condition on one day. Half the subjects were exposed to the 45° condition first, followed by the 25° condition. The order was reversed for the remaining subjects. Condition presentation order was therefore counterbalanced. A typical session took slightly less than one hour, broken up as follows: briefing and helmet fit - 10 minutes, target detection task - 12 minutes, break - 2 minutes, motion detection task - 6 minutes, break - 5 minutes, free flight and practice in attacking the target - 5 minutes plus 3 to 5 practice runs (learning trials to criterion of two practice targets destroyed), tracking and air combat task - 15 minutes.

D. Supplemental Data Collection

In addition to the performance parameters specified for each task, in Task 3 the following parameters were sampled at 30 Hz and stored on tape for further use.

1) Own aircraft airspeed, altitude, vertical velocity, roll angle, pitch angle, yaw angle, roll rate, yaw rate, acceleration (G), stick position.

2) Relational data - target range, angle off tail of target, antenna train angle, target position angle relative to helmet orientation, own aircraft heading relative to helmet orientation.

3) At the end of the experiment, a structured format was utilized to debrief pilots on their subjective impressions of the visual display.

E. Data Analysis

One Way Analysis of Variance (ANOVA) was applied to compare performance in 25° and 45° overlap conditions. Within each condition in the target detection and motion detection tasks, comparisons were made between performance with binocular presentation, monocular presentation, and left and right fields.

RESULTS

1) Target Detection

In the 45° condition, detection of binocularly presented targets was superior to that of monocularly presented targets in the overlap area (t (238) = 5.19, p = .0001) and outside the overlap area (t (174) = 3.22, p = .002). In the 25° condition, detection of targets presented binocularly was superior to that of monocularly presented targets in the overlap area (t (142) = 3.06, p = .003) but not significantly better than that outside the overlap area (t (206) = 1.88, p = .06). There was no significant difference between performance in the 25° and 45° overlap conditions per se. Within conditions, there were no differences in performance between left and right fields.

In both the 45° overlap condition (see Figures 2A and 2B) and the 25° overlap condition (see Figures 3A and 3B), detection performance was substantially degraded within about 5° of the edges of the visual fields. Moreover, performance in contralateral fields was suppressed in areas of field edge (frame) overlap. These effects were combined nearer the central viewing area for the 25° overlap condition.

2) Motion Detection

There was no significant difference in performance in motion detection between the 25° and 45° overlap conditions. Within conditions, there were no statistically significant differences between binocular and monocular fields in the 45° overlap condition. In the 25° overlap condition, however, detection of motion of binocularly presented targets was superior to that of monocularly presented targets within the overlap area (t (142) = 2.41, p = .02) and outside the overlap area (t (206) = 2.62, p = .01). In both the 45° overlap condition (See Figures 4A and 4B) and 25° overlap condition (See Figures 5A and 5B), substantial degradation in performance occurred near the edges of the fields. Among the targets in the lower horizontal row, suppression in the contralateral field in the area of field edge (frame) overlap occurred. These effects were combined nearer the central viewing area for the 25° overlap condition.

3) Target Tracking/Air Combat

No significant differences between or within conditions appeared in the third task. 219 of 240 runs ended in target destruction, indicating that the task was relatively easy.

4) Supplemental Data

Results from the structured debriefing pertaining to visual effects were as follows:

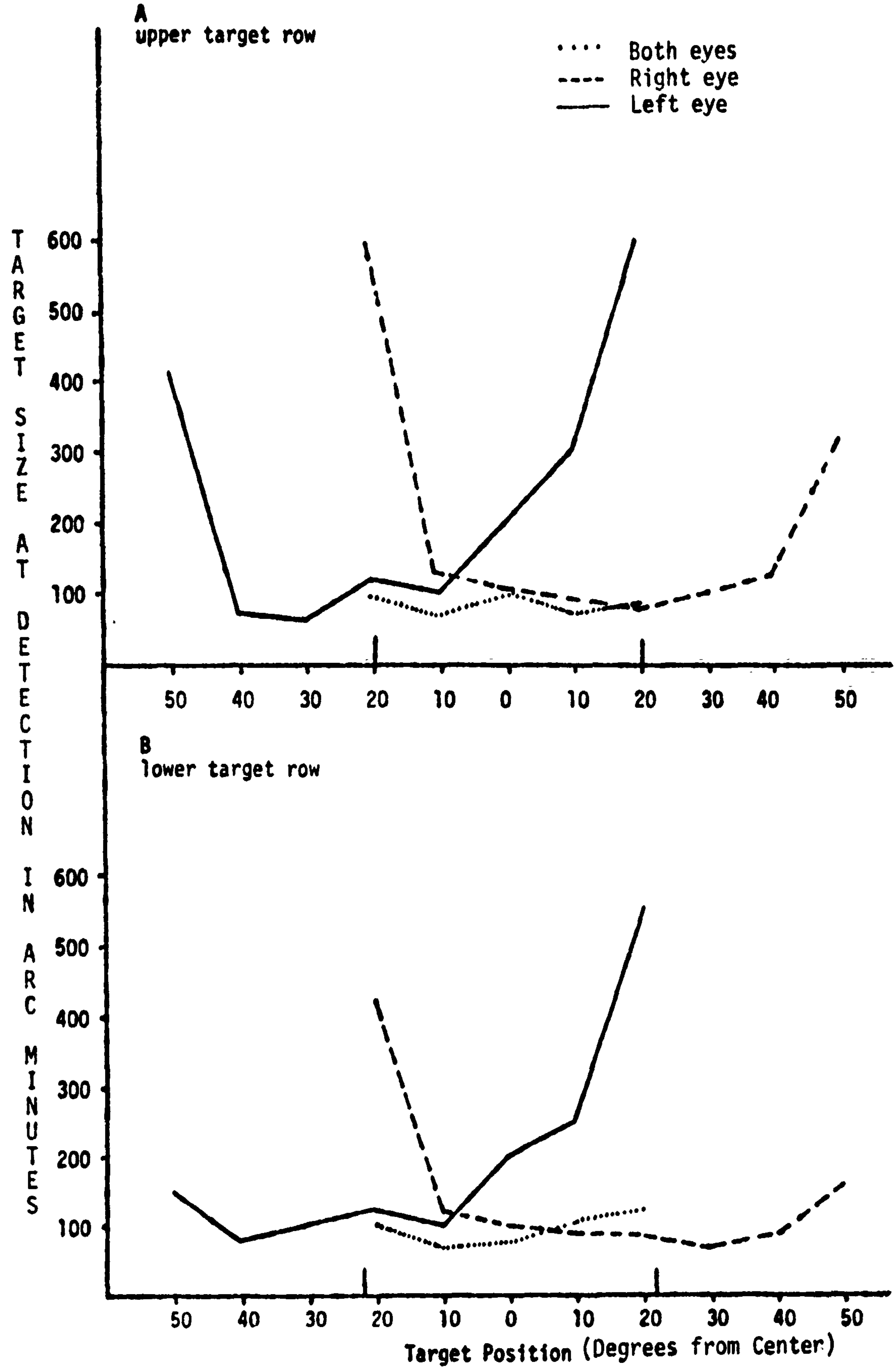

FIGURE 2. Target size at detection, 45° overlap.

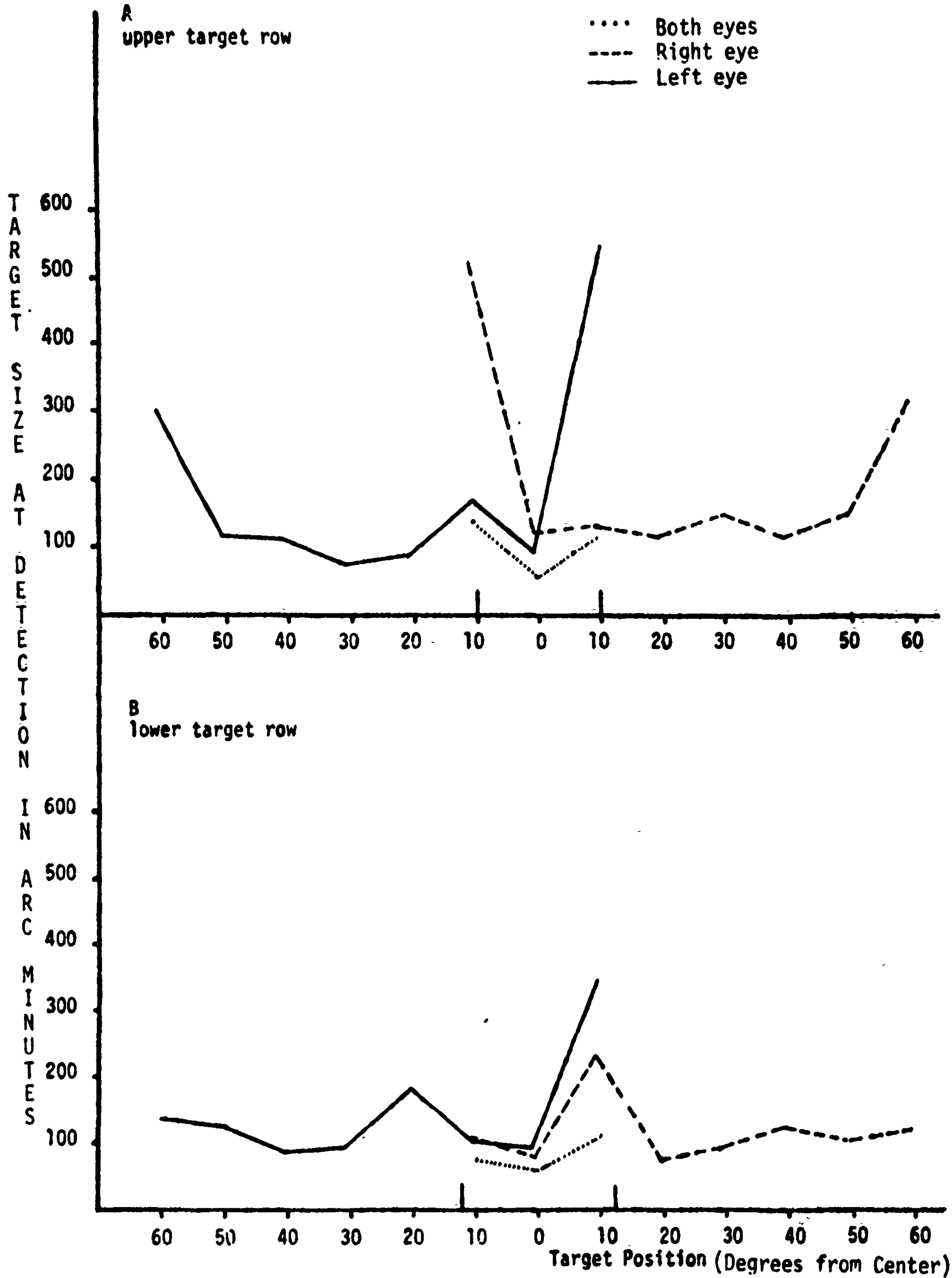

Figure 3. Target Size at Detection, 25° overlap.

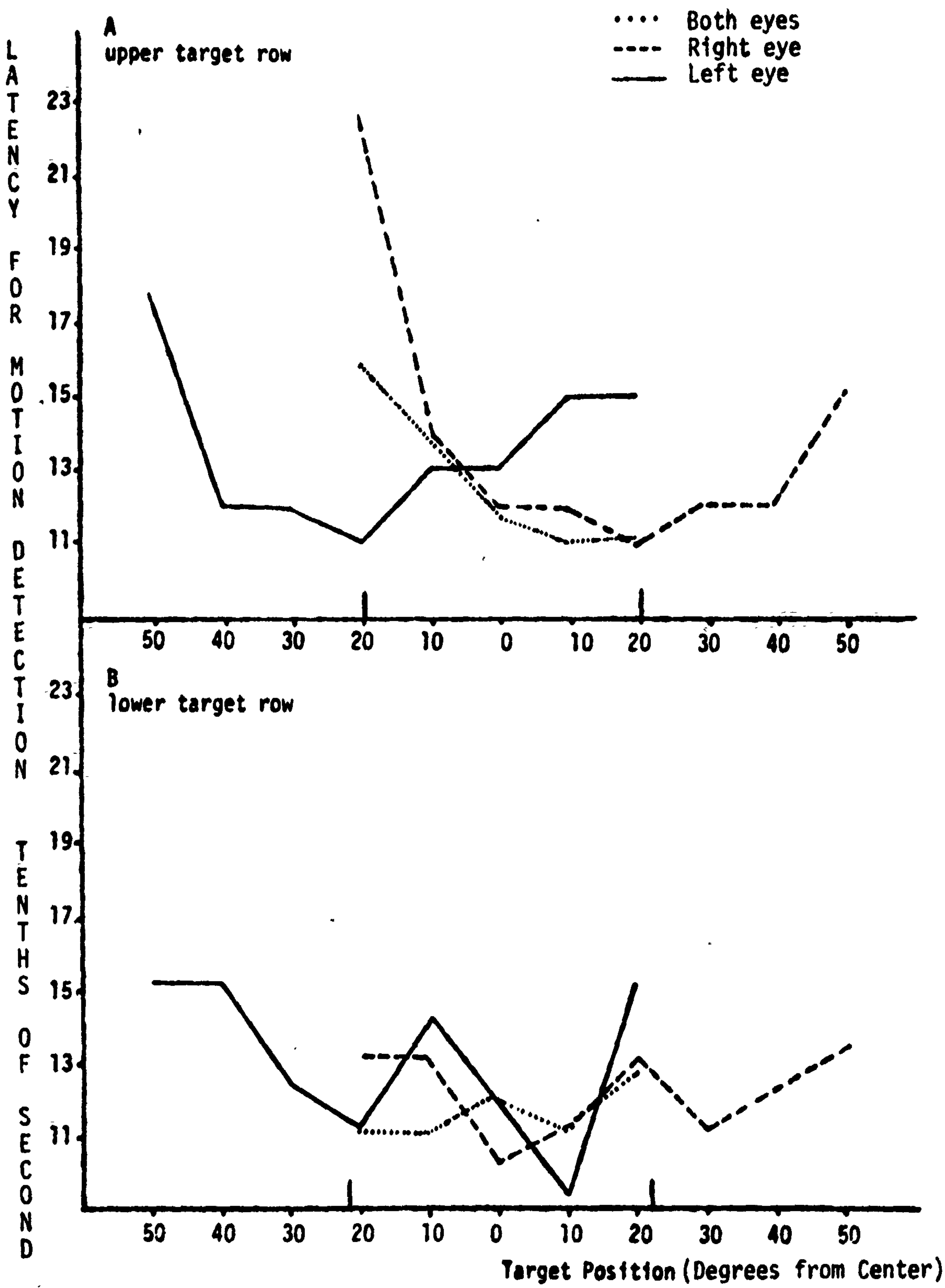

FIGURE 4. Latency for Motion Detection, 45° overlap.

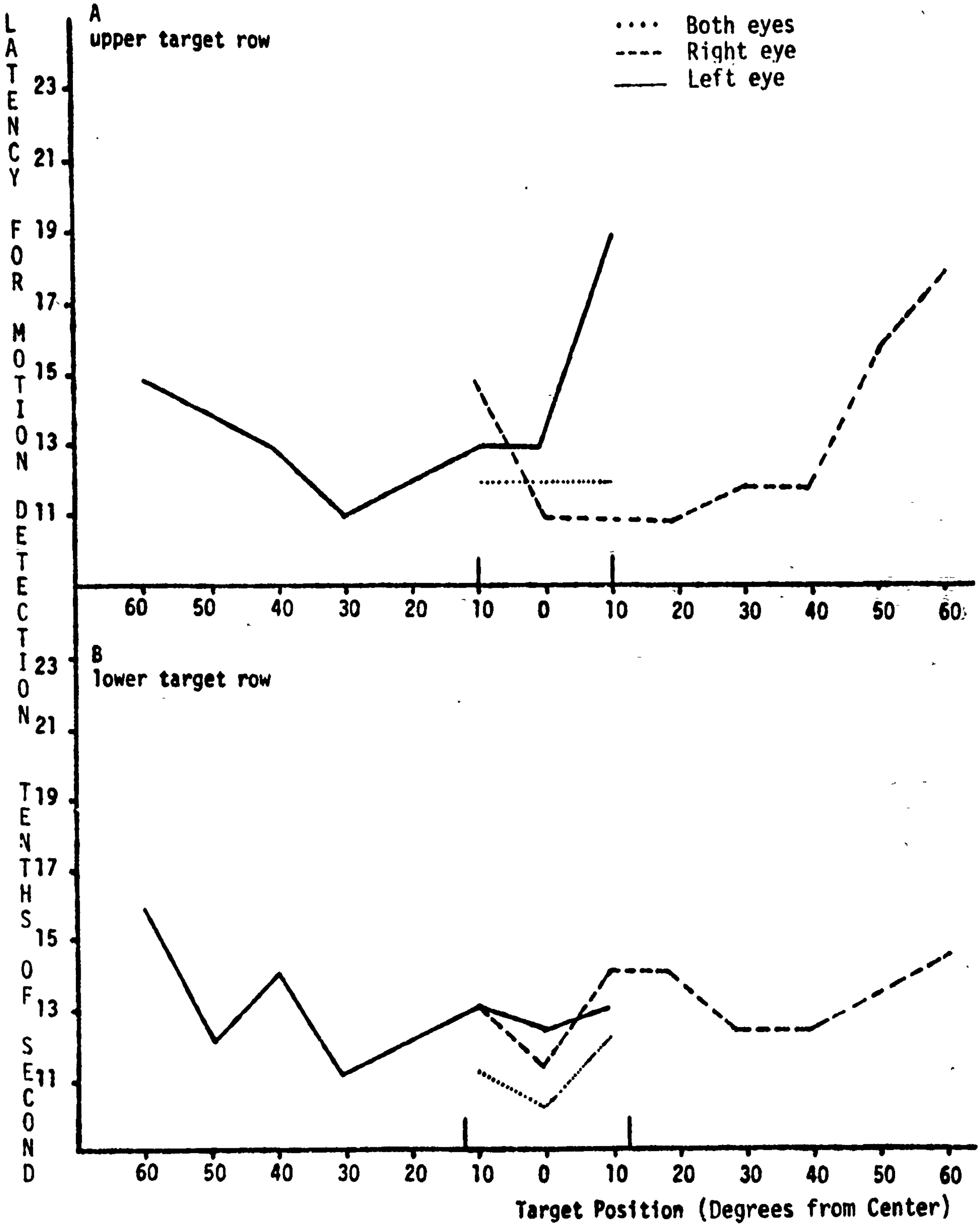

FIGURE 5. Latency for Motion Detection, 25° overlap.

1. 38% (3) of the pilots reported that the center of the binocular field in the 25° condition was truncated at top and bottom.

2. 25% (2) of the pilots stated that the width of the instantaneous field of view in the 45° condition (115°) was inadequate.

3. 63% (5) of the pilots reported that the pancake window rims were noticeable at the edges of the overlap area and 25% regarded this as a serious problem (loss of target in suppressed areas). One pilot found the fiber optic bundle structure to be distracting.

4. 88% (7) found helmet inertia excessive, contributing to loss of pupil with rapid head movements.

5. One pilot had difficulty maintaining the scene because his wide interpupillary distance (75mm) was outside the design limits of the system (56-71mm).

6. 63% (5) of the pilots reported loss of imagery during rapid head movement due to head/helmet slippage causing loss of alignment within the artificial pupil. The other 3 pilots slowed their head movements to maintain the alignment within the pupil.

7. 88% (7) of the pilots volunteered no comments about the fiber structure. When specifically asked about it, they reported the fiber structure was noticeable when the helmet was first fitted, but not when flying the system.

8. 63% (5) of the pilots found the 45° overlap condition less sensitive to loss of pupil and less of a problem for loss of target in the overlap area while one found the 25° overlap condition preferable in this respect.

DISCUSSION

1. Target Detection

The results indicated that binocular target detection was superior to monocular presentation within the overlap area, an effect which occurred for both the 45° and 25° overlap conditions. The literature on binocular detection indicates that if highly similar stimuli are presented simultaneously in corresponding retinal areas of the two eyes, summation may reduce absolute threshold below that of monocular viewing (Westendorf and Fox, 1975; Thorn and Boynton, 1974). The superiority of binocular performance within conditions appears to demonstrate this phenomenon.

This would suggest that the larger the overlap area, the better the mean performance. However, no significant difference in overlap conditions, per se, was observed. This result may be due to the fact that decrements in performance near the edge of the field were relatively large and may

have masked any advantage of 45^{o} overlap over 25^{o}. To foveate targets at the edges of the field, it was necessary to turn the eyes as much as 35^{o}, placing them right at the edge of the 15mm artificial pupil. This situation was exacerbated in the 25^{o} overlap condition, since the angles used, in effect, reduce the usable pupil width to about 12mm. Since the primary effect of sliding out of the artificial pupil is a loss in brightness at the edges of the display, degradation of performance near the edges of the fields are most likely related to reduction of brightness in those areas. There was also degradation of performance for targets displayed in contralateral fields in the areas corresponding to overlapping field edges. This effect is most likely due to binocular rivalry, since the rims of the pancake windows are black anodized aluminum and in the present system, excessively thick. A pattern at its own threshold can suppress a contralateral pattern (Blake, 1977) and these rims appear to be well above threshold. This problem was worse in the 25^{o} overlap condition since the aspect of the rim is somewhat greater at the angles used for that condition. These results are consistent with the literature on binocular rivalry effects in helmet mounted displays (Hershberger and Guerin, 1975).

2. Motion Detection

The results indicated binocular performance was not consistently better than monocular performance across conditions, but the use of threshold matched rather than standard sized targets may have affected performance in these areas, since targets which were detected late in task one were relatively large (up to 10^{o} visual angle) when presented in the second task. The use of targets slightly larger than at detection threshold (if reaction time is taken into account) for each position, for each subject, might be expected to flatten the curves in task two relative to the first task. Figures 4 and 5 indicate that this occurred to some extent, but also that brightness losses for targets near the field edges and binocular rivalry effects occurred, particularly in the 25^{o} overlap condition.

3. Target Tracking and Air Combat

The third task turned out to be relatively easy, as indicated by the overall 91% success rate. Variability in performance sufficient to determine possible differences between 25^{o} and 45^{o} overlap conditions did not occur. Furthermore, since pilots tended to center the target in their field of view when head tracking was active, and rarely lost track, the actual width of the overlap area flanking the target may have little relevance. However, flying the system as a simulator did provide subjective (pilot report) data on display characteristics. Subsequent experiments should employ a more demanding air tracking task.

CONCLUSIONS

Given that, in a head-slaved system, it is important to maximize target visibility in the central viewing area, the present findings would suggest a level of overlap larger than 25° should be utilized. The results indicated that for the existing optical configuration of the FOHMD, the 25° overlap condition was subject to greater exacerbation of binocular rivalry effects, greater susceptability to loss of the artificial pupil, and concomitantly greater potential for loss of imagery at the nasal intersection of the binocular fields. This combination of factors tends to reduce the vertical height of available imagery at the center of the display, where it is most critical, to less than the full field in the 25° overlap condition.

The results also suggest several potentially useful modifications for consideration in future system design. The degradation in performance at the edges of the displayed field, extending to actual loss of imagery with rapid head movement, could be reduced by increasing the width of the exit pupil from its present 15mm size. The contralateral field suppression effects associated with the optical frames could be partially alleviated by decrease in frame width, as well as by masking of the nasal edges of the frame contours.

A follow-on experiment is planned for the immediate future to replicate the present design with the addition of high resolution insets to the field-of-view. That experiment will address the interaction of degree of overlap, display resolution, and inset size on target detection, motion detection, and performance in a more demanding air combat task.

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PANEL DISCUSSION

"User Considerations — Where's the Beef?"

COLONEL LAWRENCE J. MURPHY, USAF
Deputy Chief of Staff, Aircrew Training Devices
TAWC, Eglin Air Force Base, Florida

Colonel Murphy was born Sept. 9, 1934, in Antigo, Wis., graduated from high school in 1952, received a degree in military science and was commissioned a second lieutenant in the Air Force from the U.S. Military Academy, West Point, N.Y. in 1957. Following pilot training at Bartow AFB, FL and Laredo AFB, TX in 1957-58, he was assigned to Williams AFB, AZ for combat crew training in the F-86F. In 1959 he was assigned to Craig AFB, AL for T-33 Basic Instructor School. From July 1959 to September 1963, he served as an instructor pilot in T-33s and T-37s at Vance AFB, OK.

After completion of F-100 combat crew training at Luke AFB, AZ in June 1964, Col Murphy was assigned to Royal Air Force Lakenheath, U.K., where he served as an F-100 flight commander until July 1967. He volunteered for combat duty in Vietnam and was assigned to Phan Rang Air Base, Republic of Vietnam, as an F-100 flight commander from August 1967 to August 1968 where he flew 308 combat missions while in SE Asia.

From August 1968 to July 1970, he served as a T-38 flight commander and instructor pilot at Laredo AFB, TX. He was then assigned to the Pentagon where he completed a four year tour as staff officer in the Deputy Chief of Staff for R&D. In September 1974, he was reassigned to HQ, TAC, Langley AFB, VA as Flight Simulator Division Chief for the Deputy Chief of Staff for Requirements. During this tour of duty, he was selected as an advance agent for Presidential Flight Support and performed numerous temporary duty assignments as on-site agent for support of Air Force One and Presidential travel support aircraft.

From September to March 1981, he served as tactical fighter branch chief and division Chief, Computer/Support Division at AF Operational Test and Evaluation Center, Kirtland AFB, NM. In March 1981 he became the assistant Deputy Chief of Staff, Aircrew Training Devices and selected as Deputy Chief of Staff, Aircrew Training Devices in April 1983.

Col Murphy has a masters degree in R&D Management from George Washington University. He is a command pilot with more than 4500 flying hours in F-100, F-86, T-38, T-33, T-37 and T-39. This includes 451 hours of combat time in the F-100. Among his military decorations are: Legion of Merit, Distinguished Flying Cross with one oak leaf cluster, Meritorious Service Medal with one oak leaf cluster, Air Medal with 14 oak leaf clusters and the Air Force Commendation Medal.

COMMANDER WILLIAM D. JONES, USN, Panelist
Staff, Chief of Naval Air Training (CNATRA)
Corpus Christi, Texas

Commander William D. Jones, USN, has served in Naval Aviation for 27 years. In addition to four tours in Attack Squadrons he has served as training officer for the A7 Fleet Replacement Squadron and Commanding Officer of an advanced jet training squadron. Currently assigned to the staff of the Chief of Naval Air Training, he has been involved with the acquisition of the 2F129 and 2B37 flight simulators; he is the staff's program manager for VTXTS and is assigned as a member of the VTXTS Source Selection Evaluation Board.

LIEUTENANT COLONEL CARL R BIERBAUM, USA
Headquarters, USAAVNC
Fort Rucker, Alabama

LtCol Bierbaum was born in Litchfield, Illinois, received his Bachelor of Science degree from Embry Riddle University and Master of Arts degree from Central Michigan University.

From July 1980 to the present, he has been assigned as Chief, Flight Simulator Division, Fort Rucker, Alabama. Flight Simulator Division is responsible for operation of all flight simulators at Fort Rucker and software support for all Army flight simulators worldwide.

MAJOR MICHAEL J. SIEVERDING, USAF, Panelist
MAC C-130 SIMCERT, 34th TATG
Little Rock Air Force Base, Arkansas

Major Michael Sieverding has been a practicing navigator since 1971 and an instructor/evaluator since 1974. He has 4000 flying hours, with over 400 hours in combat. He holds the Distinguished Flying Cross and several Air Medals.

In 1981 and again in 1983, he was chosen by USAF Chief of Staff as the USAF nominee for the Institute of Navigation technical achievement award.

He has published numerous technical articles in professional navigation periodicals and has given presentations before technical groups in both the United States and Canada.

For the last several years, as a member of the MAC C-130 SIMCERT Team, Major Sieverding has been instrumental in the development and refinement of the C-130 WST visual system.

CAPTAIN MILT MILLER, USAF, Panelist
Chief, Low Altitude Training, 162 TFG/AZANG
Tucson, Arizona

Capt Miller is a Fighter Weapons School Instructor Pilot with the 162 TFG, Arizona Air National Guard. He has over 1800 hours of fighter time and over 1000 hours of instructor pilot time in the A-7D.

He has spent the last three years developing a comprehensive low altitude training program which has received the full endorsement of Tactical Air Command, the Air National Guard, the Canadian Air Forces, and all major command Deputy Commanders for Operations.

Capt Miller has briefed over 1500 aircrews, 10 headquarters staffs, 50 general officers. He has written four safety articles, designed two syllabi, and written a 250 page training manual. He just completed writing, producing and narrating a 30 minute videotape on low altitude flying for world-wide Air Force distribution.

He is currently writing the second edition of his manual and preparing for a second videotape on visual illusions.

CAPT JOHN R. ELLIOTT, USMC, Panelist
Marine Corps Air Station
Yuma, Arizona

Captain John R. Elliott was born August 24, 1951, in North Babylon, New York. He graduated from high school in North Babylon and received his Bachelor of Science Degree from Cornell University.

After commissioning in May of 1973 and completion of The Basic School, he was assigned to flight training in Pensacola, Florida, and received his wings as a Naval Aviator in May of 1975.

After completion of replacement Aircrew Training in the F4J, Capt Elliott was assigned to VMFA-251 in Beaufort, South Carolina, and subsequently deployed to the Western Pacific with VMFA-122. In September 1979, Capt Elliott was assigned as an F4 instructor pilot in the Marine Corps' Fleet Replacement Squadron, Yuma, Arizona, and is presently serving as Assistant Training and Education Officer for Marine Corps Air Station, Yuma, Arizona.

Over the past eleven years, Capt Elliott has flown 1800 accident free flight hours in the T-34, T-2, TA4, F4 and C-12 aircraft.

MR. KINGSLEY POVENMIRE, Panelist
Training Advisor
U.S. Coast Guard Air Training Command
Mobile, Alabama

Mr. Kingsley Povenmire received his M.S. degree from the University of Illinois in 1972. From 1968 to 1973, he served as Director of Research Flight Operations at the University's Institute of Aviation, Aviation Research Laboratory.

He has published several papers including a flight training evaluation of the new concept of Transfer Effectiveness conceived jointly with Dr. Stanley N. Roscoe, Laboratory Director.

For the past ten years, Mr. Povenmire has been Training Advisor at the U.S. Coast Guard Aviation Training Center. He has been involved in developing visual training requirements for new fixed wing and helicopter simulators.

Mr. Povenmire has over 4000 hours as a civilian flight instructor and is current in the Cessna 152, 172 and Mooney M20C.

SESSION VII
Psychological Considerations

DR. CONRAD KRAFT, Session Chairman
Professor, University of Washington
Bellevue, Washington

Conrad L. Kraft, former Chief Scientist, Crew Systems and Simulation, Boeing Aerospace Company. His Ph.D. is from Ohio State University in Engineering Psychology and his M.A. and B.S. are from the University of Wyoming in Experimental Psychology. His 37 years of professional experience has been in industry, academia and the military. He was the scientific liaison between O.S.U. Research Foundation and the Aero-Medical Laboratory, Wright-Patterson Air Force Base, Ohio (1952-59) before going to Boeing in Seattle. With Boeing he was particularly interested in aviation safety and most recently chaired the committee which developed the specifications for Boeing's Flight Crew Training Simulator's Computer-Generated Visual system, the Compuscene built by General Electric.

Dr. Kraft is presently a professor at the University of Washington, Seattle.

BAFFLED EYE AND CONFOUNDED BRAIN
or
USING VISUAL ILLUSIONS TO TRAIN BLIND PILOTS

Robert E. Clapp received his BSc and MSc from the University of London. During his 28 years of industrial experience he has been involved in optical and visual systems. During the last 15 years he has become involved chiefly in simulation activities and systems. Currently employed by the Boeing Military Airplane Company (Wichita, KS) he is engaged in visual systems in simulation and other optical and visual work. He has worked for both Sperry/SECOR and Singer Link and was at the NASA Houston Facility for several years.

BAFFLED EYE AND CONFOUNDED BRAIN
or
USING VISUAL ILLUSIONS TO TRAIN BLIND PILOTS

Abstract:

The extremely simplified and stylized scene construction in current computer image generation technology, together with scene dynamics shortcomings present display technology with a grossly inadequate real world simulation (one that can be truly called illusionary). Nor is current display technology in better shape. Due to confusion existing within the simulation industry over resolution of the displays, visual systems are underspecified or underdesigned by a factor of about 4 times. This is in addition to low brightness and contrast of saturated colors. If the pilot saw in the real world what he sees in the simulator he would be legally blind! These factors are discussed in some detail and possible improvements are suggested.

Introduction:

The techniques of visual simulation must satisfy the observers eye. This statement is as obvious as its neglect is stunning. Currently visual systems are being specified (correctly) upon the basis of what can be produced technically, then this state-of-the-art technology is accepted (incorrectly) as standard for the observers eye.

Two major sets of factors determine the performance of the human visual system. One set comes from the physics of light, the laws of optics, parameters of materials and the engineering principles uniting these parameters into the device called a simulator. The second set comes from the psychophysics of vision and the perceptual processes adapted by the human observer.

Schade points out: "The psychophysical factors came first.....ranking (picture) quality according to 'graininess', 'gray scale', and 'resolving power' long before the objective equivalents were understood correctly; simply because the psychophysical factors are determined by direct observation. Even very old data on the eye are still valid because the eye has not changed for a thousand years."

"The correlation with objective factors, however, has required much experimental work with images of precisely known objective factors (signal, noise, MTF) which have been found to determine what we can see: resolving power, gray scale at any contrast, illumination and gray scale value."

The discussion in this paper will be limited to computer generated image systems. For comparisons of other systems see Reference 1, 2.

Discussion I:

How the eye sees (Real World)

This section summarizes the performance of the eye in the real world.

Vision is the primary sensor for derivation of real world data, providing the bulk of our sensory knowledge of the real world. Vision performs the dominant role in human spatial orientation. The visual sensory system combines with the other body senses to provide a visual/vestibular/kinesthetic sensor interaction: postural and vestibular/ocular reflexes stabilize the retinal

image (without stabilization, visual acuity is greatly reduced). The acquisition of visual cues depends upon interplay of various sensor systems to establish where to look for cues. The perception (by the pilot) of the visual cues and his application of the cues to his operational processes depends upon recall from memory and comparisons to current cues. If the perceptions are predictive (as many are) and/or the information (stored or current cue) is limited, the operational processes of the pilot will be subject to limitations (errors, illusions, etc.).

The concept of dual mode processing of visual information has received considerable (and increasingly complete) support in work done over the last 15 years. While the neuroanatomical considerations are beyond the scope of this paper (and also the competence of author), the functional operations are well understood and give a unified picture of the visual processes employed. These dual modes are:

First, the Focal Mode: In general this mode answers questions of "what" - object recognition and identification. The focal mode involves fine detail (high spatial frequencies), typically represented in the central portions of the visual field (fovea and neighboring area of retina totaling about 12° from axis of eye). The information supplied is well represented in conscious mental processes and is critically related to physical parameters such as stimulus energy. Most of the studies relating to "vision" as well as most tests for evaluating individual visual performance are concerned with "focal" mode functions.

Second, the Ambient Mode: In general this mode answers questions of "where" - object localization and orientation with reference to the observers perceived spatial organization (or alternately for locating and orienting observer with regard to external spatial organization). Ambient vision involves large stimulus patterns, typically represented in peripheral visual fields and relatively coarse detail (low spatial frequencies). Unlike focal mode vision, ambient vision is not systematically related to either stimulus energy or optical image quality. Provided only that the visual stimulus is sufficient to be visible (absolute brightness and contrast) ambient mode operation appears to be on an "all or nothing" basis. Because subcortical structures are involved, the conscious awareness of the ambient mode operation is low (and frequently absent). Interest in this subject has always been high, but little work was done prior to the last 15 years.

In the continuous visual perception process, the ambient mode would establish and maintain relative pilot orientation, and would "tell" the pilot "where" to look to establish detail recognition and identification. Thereafter the visual scene parameters are maintained in the pilots "operational perception" by a combination of ambient and focal mode information processed in combination with the pilot's memory of the factors involved in past experiences. The extraction of visual information from a visual scene is a lengthy task involving continuous ambient and focal mode information input to a mental perceptual construct that continually asks what, where, who, how, etc. In the conscious (and unconscious) scanning of a visual scene, the observer traces outlines of objects of importance, then concentrates attention on those objects (or parts of objects) which by the observers valuation produce the most relevant information. (This assumption of value is involved with pilot's experience, current operational parameters, mission briefing, etc.) See Figure 1 for a flow diagram of the process.

An important aspect of these two visual modes is that their processing (within an observer's brain) can be dissociated (e.g., walk while reading) without apparent disadvantage. The focal mode appears to be largely independent of other sensory inputs (i.e., little disorientation results from vestibular, etc. interactions), except for other visual (ambient mode) inputs. Conflicts between focal modes and ambient modes appear to destabilize the focal mode, causing confused focal mode inputs to the visual processing operations. Conflict between ambient visual mode inputs and other sensory inputs (vestibular, etc.) produces disorientation. Severe mismatch produces nausea, etc., which apparently serves as a warning of dangerous environmental conditions and/or inaccurate orientation cues. Additionally "short circuits" are provided to bypass conscious thought (reflex actions) in emergency situations.

The application of these modes to pilot training problems would indicate that orientational placement of the aircraft is largely the result of the visual ambient mode operation while the detection of relative ground velocities and recognition of scene detail are largely a result of the focal mode. The analog of the pilot situation would be in driving an automobile where the general status of vehicle operation is mediated by the ambient mode, while obstacles avoidance and overtaking judgements are mediated by the focal mode (for non-drivers - walking through a crowd while reading a book). In fact the entire process of walking (subconscious control) is mediated by the ambient mode - there is evidence that children are unable to operate in the focal mode until well after ambient mode is available to them (or is this a brain memory file problem?). For more information on these processes refer to References 3, 4, 5.

Seeing is a learned ability, indeed learned at such an early age that most of the processes proceed at a subconscious level. One of the purposes of any training methodology is to improve, as far as possible, the visual processes to the limits imposed by the nervous system. The process of seeing is a perceptual one affected by and incorporating other sensations, emotions, learning, memory and other associational mechanisms. The interrelationships are many and are not well understood. Seeing varies with the individual (indeed within the individual) and the standards must be treated as statistical parameters rather than absolute values.

Perception has been defined as a complex association within the field of consciousness, made up of sensory impressions, crosslinked, supplemented by memory, and augmented by training. The perception of objects in the real world (scene detail) depends upon the parameters of the surrounding physical world, the observers present and past adaptation and the observers present and past actions.

The perception of scene detail proceeds in a continuous sweep of operation as a function of object size and range. At any distance the eye sees resolved objects (detail) and unresolved objects (texture). As the distance decreases, the eye constantly transforms the texture into resolved scene detail: this process never ends.

The following are some characteristics of the human visual system (Refs 6, 7). Also see Figure 2.

§When the eye sees a bright empty field of view, lacking in detail, the eye tends to focus at a "rest" position (about one meter). This is called "Empty Field Myopia". This factor is an accommodation "trap" (Mandelbaum effect), and can cause problems in locating intruders. Windscreens are

typically located about one meter in front of the pilot, the window frame and scratched or dirty windscreen can act as a focusing trap for the pilots eye. When the field of view is dark, this effect is called "Night Myopia" (dilated pupil and Purkenje effect contribute). The pupil decreases in size in 5-10 seconds and increases in size in 5-10 minutes: it takes much longer to dark adapt the eye than to light adapt it. The eye can see from a few quanta (2-8 photons) to about 0.01 ftL (Scotopic or rod vision) and from about 0.006 ftL to about 10,000 ftL (Photopic or cone vision). The region where both rods and cones contribute is from 0.01 ftL to 0.1 ftL (Mesotopic vision).

§Limiting resolution for the eye, based upon Rayleigh Criteria is about 0.5 arc minutes (this is strongly dependent upon brightness). This resolution is for dark spots, light spots can be resolved at all times (subject to diffraction and irradiation effects) if the brightness exceeds 8-10 photons and contrast ratio is over 3:1. Extended images can be seen where subtended size and orientation are correct (the eye is most sensitive to horizontal and vertical structures, less sensitive to diagonal structure, (this neglects visual astigmatic effects)). Wire against the sky can be seen at 0.5 arc seconds subtend (V or H), at 1.5 arc seconds subtend (diag). Vernier alignment is possible to 2-5 arc seconds subtend (precision). Stereoscopic detection is possible to 2-5 arc seconds subtend.

§The eye is strongly sensitive to motion, any relative motion in the visual scene is easily detected. The eye tries to "connect points", e.g., to image dotted lines or regular structure as straight lines, and consider continuous flashing lights as "line drawings". Sampling process (illusionary) also occur if the eye or the scene is in motion: certain elements may be picked out of context and remembered in incorrect structure - when realized this can cause considerable lost time in attempting to "resee" the effect.

§Visual orientation and alignment is dependent upon vestibular and other body senses. The brain maintains an orientation and positional reference that is body centered and to which the visual system is referenced.

§Binocular vision is of major importance in judgment of distances (to about 6000 ft). Additionally brightness, resolution, size and color judgments are affected by presence or absence of binocular cues. Binocular vision is a maximum at about 20° of arc from the actual axis of the eye (line of sight).

§The eye is subject to an effect known as Chromostereopsis. When viewing unsaturated colors, the tendency is to view red or blue as closer. In the real world the superabundance of distance cues and the presence of unsaturated colors greatly reduce this problem (most persons are unaware of the effect). Do pilots on overwater (or limited cue) approaches at night land in water (or short of runway) have "red closer" chromostereopsis?

§Size of objects viewed is prefered by the eye to be 2.5 to 3.5 cycles (line pairs) per degree for each object or about 20 to 30 arc minutes object subtend.

Discussion II Simulation:

Viewing the Simulation Display

An observer viewing the simulation display (after experience in the real world) is struck by several factors:

§Brightness of display is very much less than in the real world even for night scenes, but is particularly noticeable for daylight flight. This factor

does improve acceptance of the simulator display for night flight (due to degradation of observers visual parameters because of reduced light levels, see Figure 1). To present satisfactory day simulation requires a considerable increase in display brightness, by a factor of 100 times.

§Lack of scene detail and presence of straight line constructs cause a cartoonish appearing display, again most noticeable in daylight presentation. The fine detail and texture of the real world is missing. The displayed picture does not transition through the texture to object sequence of the visual real world field of view. This problem is worsened by the presence of straight line or regular circle structure and largely saturated colors, which impart a certain garishness to the display.

§Lack of resolution causes a generally fuzzy appearance to edges of objects in the field of view, producing a feeling of spurious scene detail.

§Scene dynamics does not appear correct. Motion cues do not seem to be occurring as in the real world. Objects in the field of view do not shift in proper relationship to the surrounding objects, and do not "rotate" as in the real world.

§Binocular cues and scene construction are missing. Most observers are too familiar with "normal" motion picture and "normal" television, having been conditioned to accept flat pictorial representation of the viewed scene. Use of infinity (virtual image) displays makes a considerable impression of depth in the display, but when objects are approached closely, the lack of true stereoscopic cues is very noticeable.

§These details are discussed in the following sections, several other effects are not (principally image defects, e.g. aliasing, scene breakup, etc.). Despite these discussions it is apparent that computer generated image systems represent the most promising approach to visual simulation (see Ref 1, 2). This is because of the versatility of the CGI approach with large gaming area and the possibility of hybrid systems that combine the best effects of CGI with other techniques.

§The question of suitability of display for training purposes is, of course, within the bailiwick of training specialists. Still the entire thrust of development of simulation systems has been to increase fidelity of the systems, and each increase in fidelity has meant an increase in training effectiveness. Nor has this been entirely a matter of higher cost, it is possible to increase fidelity and <u>decrease</u> cost. (See Refs 8, 9, 10)

§Current computer generated image displays can be used for familiarization training (~100% effective), for initial training (~30% effective), and for continuation training (~10% effective). When pilots have progressed from simulator to real world aircraft, the training transfer is high (~90%); when returning to the simulator, their training transfer is very small (~5%). The pilot learns to "fly the simulator" again, in distinction to real world flight, which presents a large amount of negative training. (See Ref 10)

Resolution of the Display

Resolution is a term subject to considerable misunderstanding and misuse. The meaning defined here is the limiting resolution of the visual display required to perform the following visual tasks:

§Detection (minimum resolvable):
An object can just be seen - "something is there".

§Orientation (minimum for aspect):
Object length/width can be seen - "horizontal is longer".

§Recognition (minimum for separation):
Object class can be determined - "it is an airplane".
§Identification (minimum for identifying object):
Object can be determined within class - "its a B-52".

For example the letter E can be resolved by the eye at 0.5 to 1.0 arc minutes, the actual size of the letter E is 2.5 to 5 arc minutes. Normal 20/20 vision is defined as the ability to see the resel (subtend 1 arc minute) of the letter E, the letter itself is 5 resels or 5 arc minutes.

In most simulator systems the resolution of the visual display is limited by the display system. For our purposes here, the display system is defined as a raster type (TV monitor or TV projector) and the system resolution is 3 arc minutes per TV line.

Resolution requirements of visual displays have been studied extensively. Table 1 presents the summary of Johnson's work. (Refs 11, 12)

TABLE 1

Resolution per minimum dimension (in line pairs) After Johnson

	Detection	Orientation	Recognition	Identification
Resolution Required	1.0 ± 0.25	1.4 ± 0.35	4.0 ± 0.8	6.4 ± 1.5

Here the targets were of high contrast and the values obtained were for 50% confidence level. (Note 1 line pair = 1 cycle = 2 TV lines).

These criteria have been used for many years in the visual display field (see Reference 12) except in the simulation industry. By these standards our display system would require:

For detection: 6 arc minutes (2 TV lines).
For orientation: 9 arc minutes (3 TV lines).
For recognition: 24 arc minutes (8 TV lines).
For identification: 36 arc minutes (12 TV lines).

These results are confirmed by studies which found requirements of 6-8 TV lines or 18-24 arc minutes on the display for identification of military and civil objects (aircraft, oil tanks, bridges, buildings, etc.). Reference 13, 14, 15, 16

From this the resolution requirement for the visual display is established as 1/4 or 1/6 of the required training task support resolution. Our 3 arc minutes display would provide 24 to 36 arc minutes resolution to an observer for recognition/identification tasks. Note this is for high contrast targets.

On the example of vision standards note that for our system to draw a letter E would require 7 TV lines or an angular subtend of 21 arc minutes, this corresponds to a visual acuity (Snellen test) of about 20/160 or a legally blind observer).

Computer generated visual scenes require some sort of display system. As the image generation part of the visual scene, there is no limit on the resolution (CGI systems can generate a mathematical point of line), but this image must be displayed to the observer. It is apparent that the limitation of resolution will be the display system. Display technology has lagged over the last several years and requires new approaches as well as increased refinement in current methods. Systems capable of 0.5 arc minute resolution should be the goal.

Note on resolution of raster systems: Some semantical problems are involved in resolution when speaking of raster systems. Vertical resolution is determined by the raster stucture (sampling line scan or display). Horizontal resolution is a function of system bandwidth. Both values will be nearly the same (if different the imaged object will present distortion structure to the observer). Hence speaking of resolution of 3 arc minutes implies vertical and horizontal resolution is the same. (See Ref 12)

Scene Detail

Scene detail or texture may be added to the visual scene only as a discrete multiple of the minimum resolution capacity of the display (in our case 3x3 arc minutes). Since the eye is capable of much finer ersolution, the presented visual scene will be totally lacking in any high frequency components (no texture or detail of less than 3x3 arc minutes). The scene will appear cartoonish. The comparison between our display system scene and the real world scene is presented in Table 2.

TABLE 2

Simulator/real world comparison (for field of view 50x40 degrees)

Factor Minimum Resolution	Simulator Display 3 arc min/TV line	Real World	Simulator Performance as % of Real World
Element	3x3 arc min 9 (arc min)	2x2 arc sec 4 (arc sec)	0.012%
Detection	6x6 arc min 36 (arc min)	2x2 arc sec 4 (arc sec)	0.0031%
Orientation	9x9 arc min 81 (arc min)	4x4 arc sec 16 (arc sec)	0.0054%
Recognition	12x12 arc min 144 (arc min)	16x15 arc sec 256 (arc sec)	0.049%
Identification	19x19 arc min 361 (arc min)	30x30 arc sec 900 (arc sec)	0.069%

Generation of scene detail/texture is a computational problem in computer generated image systems (if the display problem is resolved) and so is a question of sufficient computational capacity.

One method commonly adopted to improve detail appearance is to use texturing (unresolved detail) approaches to give the illusion of increased detail. The texturing algorithms are periodic, and must be selected with great care to prevent aliasing problems, particularly under dynamic scene presentation. The goal of such procedures is to cause the observer's mental processes to conclude his eye is at fault and not the display. Adding scene detail at 3 arc minutes should not be taken as implying that this scene detail can be resolved by the observer. The question of scene detail resolution is strongly dependent on contrast, lighting, etc and normally requires 1 cycle (line pair) or 2 TV lines as a minimum.

Display Dynamics

Many descriptions of the real world scene dynamics have been presented (Ref 11). Basically these are motions of objects in the field of view resulting from the movement of the observers eye. Moving the eye through the field of view

presents a different dynamical structure than moving the field of view past the eye. In the real world scene dynamics are a combination of two effects: vector motion of the eye and dynamic interactions resulting from the direction of the observers line of sight.

In a simulator display the visual scene generated is based only upon the vector direction of the observers eye, hence only when the observers eye line of sight is directed along the vector of motion, is his scene as viewed correct. If the observer looks anywhere else in the display, the scene will present incorrect cue motion.

To correctly present these scene cue requirements would require considerable computational power as well as some method of monitoring (and anticipating) the pilots line of sight. Presently little effort is being expended on this problem.

Stereoscopic Displays

Judgement of size and distance is critical in many simulation training tasks, and so requires stereoscopic displays. Of particular interest are the tasks associated with aerial refueling, tactical formation flight, ground attack and low level missions (also possibly landing). Presently stereoscopic displays are beyond the state-of-the-art (except for direct optical projection displays, which are severely limited in gaming area and suitability for incorporation on motion base). Stereoscopic display technology has not advanced much beyond the anaglyphic or polaroid systems. The gain in display system acceptance and performance certainly merits considerable effort in development.

Saturated Colors

Present computer generated image systems are limited in colors to largely saturated hues. This contributes to the cartoonish appearance, and also produces an effect known as chromosteropsis. The general population will observe red or blue colors as closer, depending on saturation levels and presence of other stereoscopic cues. In the real world this problem arises rarely, but is of frequent occurrance in a simulator. Incorporation of unsaturated colors improves the situation. This can be aided by enabling the display to produce directional illumination effects, especially specular and diffuse reflection patterns (a data base/algorithm problem for the CGI).

Brightness of Display

As with resolution this is a display problem, requiring new or improved light sources or projection techniques. Considerable work is under way in these areas. Brightness of the display should be at least 100 ftL as a highlight maximum.

Summary and Conclusions

The techniques of visual simulation must satisfy the observers eye. Acceptance of the visual display by the observer is largely subjective, conditioned by the observers training an dexperience (and also the answer to the question: Is this the best that can be done?). Some visual simulation systems will present special features to give better scope for training tasks (e.g. aerial refueling), but CGI systems, because of their flexibility and available gaming area (despite their shortcomings), offer the best all around visual simulation systems. Current state-of-the-art is advancing in the field of hybrid systems, whose combination with CGI technology will present a display that takes full advantage of the CGI capability while compensating for several of the defects. (Ref 1, 2)

Currently, however, caution should be exercised in the evaluation of display systems used with CGI systems: The system does not present a display that allows the observer to see well enough to distinguish required detail for many training tasks. While this presentation may be the best available (and so is used), the display quality is poorer than a legally blind person would see in the real world. These factors should be considered in establishing training requirements and training syllabi.

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Notes on Figure 1 "The Pilots Sensor-Processor-Decision-Action Flow Diagram" Visual Operation

The pilot receives sensory inputs from his visual system(s), focal and ambient as well as other body sensor systems (gravitic, positional, motion, acceleration, etc.). These sensory inputs are combined (the body sensors and ambient visual serving to stabilize the focal visual inputs and to orient the pilot to his world status and situation). These input cues are combined by the pilots mental proceses with past situational memories, training conditioning and emotional factors to form a "Trial Hypothesis". This hypothesis directs to focal visual system to look at some pattern, structure or object in the visual field (or possibly the focal mode continues to scan the display under general program instructions). On the basis of these inputs and the other sensory and memory inputs a new "Trial Hypothesis" is formed, directing in turn a new "look" pattern. This process continues through a few or many cycles until the pilot attains an acceptable (as determined by training inputs or mental memory) integration and recognition of his circumstance. This is followed by the pilots decisional process, his transformation of decision to action.

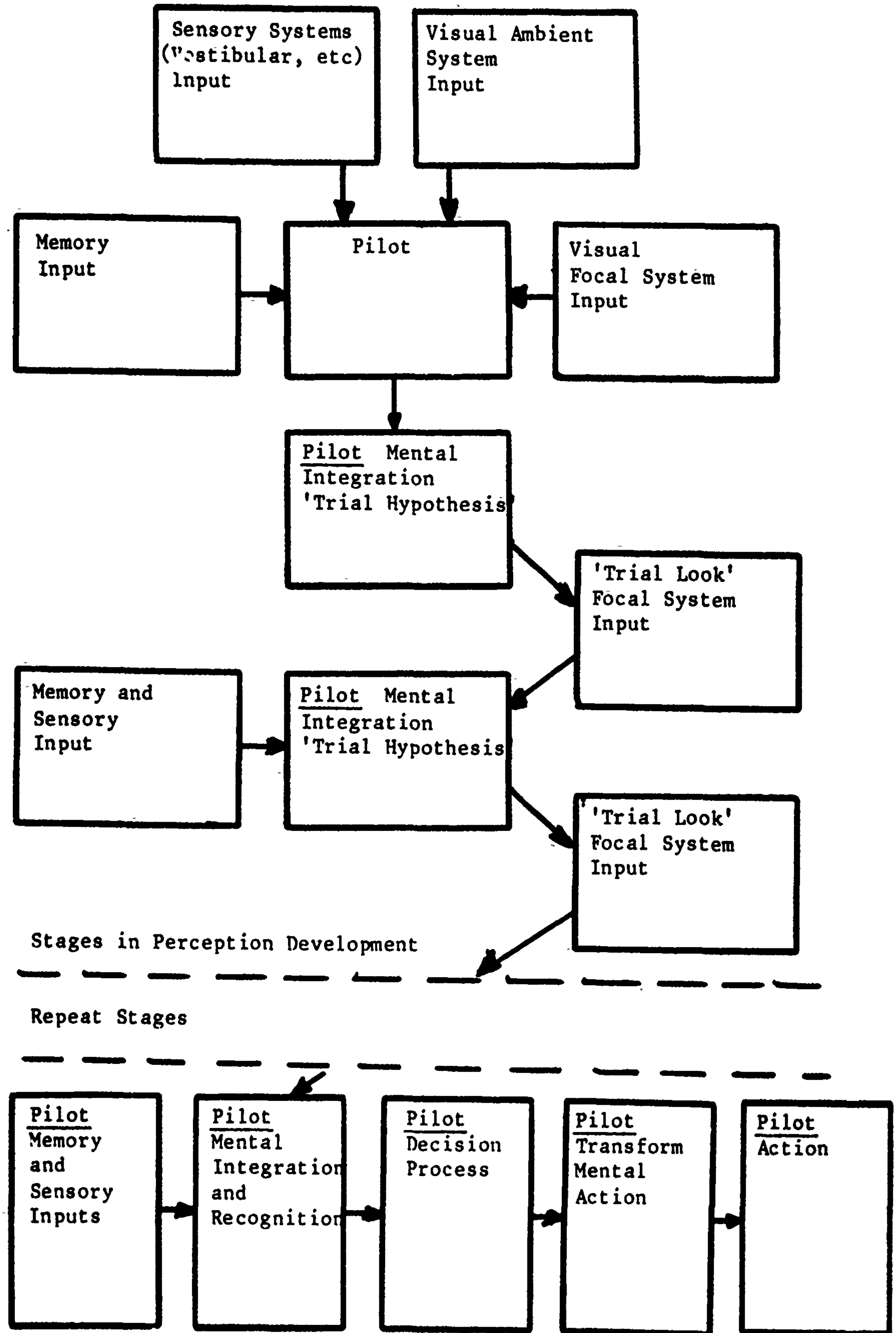

Figure 1 The Pilot's Sensor-Processor-Decision-Action Flow Diagram Visual Operation

Notes on Figure 2 "Visual Parameters: Real World Eye and Simulator Display"

The parameters for the "Real World Eye" curves 1, 2, 3, 4, 5 are from P. Webb, (ed) Bioastronautics Data Book NASA Washington, D.C. 1964 (Data are from several different studies).

1) Minimum resolvable: This is the minimum object size that can be resolved by the human eye (minimum is 0.5 arc seconds).

2) Stereo minimum resolvable: This is the minimum resolvable that retinal disparity can attain for two distant objects (2-5 arc seconds).

3) Vernier (alignment) minimum resolvable: This is the minimum resolvable alignment displacement between two line segments (2-5 arc seconds).

4) Recognition (minimum separable): This is the minimum for recognition (separation) of a segmented object (minimum is 0.5 arc minutes). This is the standard Snellen or Landholt figure measurement for visual acuity test. Standard 20/20 vision is considered as resolution of 1 arc minute (Snellen E or Lamdholt C) subtending 1 resel (or element) of the E or C, where the total figure is 5 resels in height. (Resel = resolution element)

5) Identification: This is considered to be 2 x recognition value (#4). Note that all parameters are stonrly dependent upon field of view brightness for values less than 10 ftL (values are nearly linear for values greater than 10 ftL until irradiation effects set in at about 1000 ftL).

6) Plotted from our "defined visual display": Minimum element is 3 arc minutes. This is the minimum size of any object or texture component that can be presented.

7) Area plot for recognition (4 x minimum element (#6)) and identification (6 x minimum element (#6)). Some simulation presentations would equate recognition with identification (high contrast aircraft). For low contrast objects identification would be more difficult and require more TV lines.

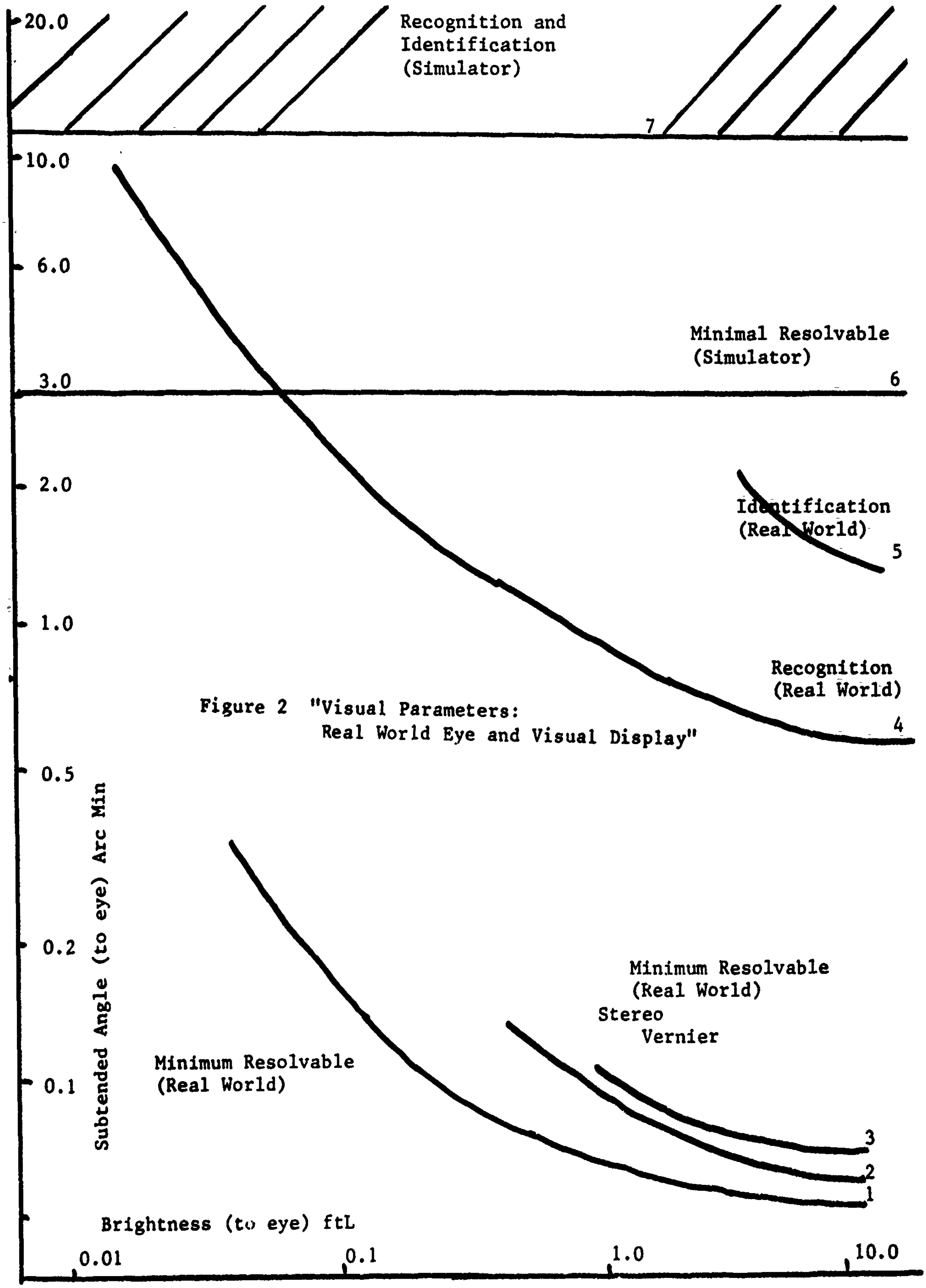

Figure 2 "Visual Parameters: Real World Eye and Visual Display"

GLOBAL OPTICAL METRICS FOR SELF-MOTION PERCEPTION

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Lawrence Wolpert obtained his M.A. in Experimental Psychology from the Ohio State University in 1983. After receiving his B.A. in psychology from Tel Aviv University, he worked in human factors R&D with the Israeli Ministry of Defence for two years. He is currently working toward a Ph.D. degree in the area of visual perception and self motion.

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GLOBAL OPTICAL METRICS FOR SELF-MOTION PERCEPTION[1]

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During locomotion, the entire optic array along the path of travel is continuously transformed. The nature of the transformations is informative about changes in altitude, speed, and imminence of contact with environmental surfaces. Some global optic-array variables are self scaled and some are environment scaled. By unlinking the two types of variables we have been able to empirically assess their relative usefulness for detecting change in altitude and speed. Determining the perceptual effectiveness of optical sources of information also tells us what the functional metrics are for detecting and guiding self motion.

The critical distinction between the two major contemporary approaches to the study of visual perception hinges on whether the information available in the light is considered adequate to account for perceptual phenomena. Theorists who consider retinal image reference systems for space and motion argue that the two-dimensional representations are inadequate to account for perception and therefore must be processed to reproduce three dimensions over time. As a result, the functional metrics of visual stimulation must be described in a retinal coordinate system <u>extrinsic</u> to the event perceived. Mediating mechanisms that process, analyze, compute, interpret, etc., are proposed to "recover" the nature of the event.

The more conservative approach begins with the assumption that there <u>is</u> adequate information in the light to account for visual perception. If so, the reference system for both the layout of space and the perceiver's motion through space must be <u>intrinsic</u> to the event perceived. That is, the coordinate system and its metrics must be specified in the event itself by the constraints the event imposes on the optic array transformations and invariants. It is further assumed that visual perception is anchored to the optic array, not to the retinal image, so that effective visual stimulation and its metrics must be defined and quantified in optic array terms.

Part of the program of the IMAGE II conference consisted of a debate in which participants responded to the question "Is the eye sufficient to see?" In spite of the labels "pro" and "con," all of the speakers agreed that the eye was not sufficient for a common reason: there is more to the visual system than the eye, and the contributions of other nervous system processes must be considered in a complete account of seeing.

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Our research program is an extension of an approach developed over a period of more than 30 years (Gibson, 1947-1979) which explores a very different reason for the insufficiency of the eye in understanding visual perception. From the ecological perspective, an account of seeing must consider what is seen, because seeing requires something to be visually apprehended, as well as someone to do the perceiving. Seeing denotes visual specification of a relationship between the individual and the surrounding environment, rather than just nervous system activity or the experiential manifestation of such activity. What must be seen in order for an individual to survive shapes the nature of the eye and visual system mechanisms, and in turn the eye and mechanisms constrain what can be seen. The eye has a very specialized role in seeing, but its function must be reconceived if perceiving is redefined as the pickup of information specifying the nature of the environment and the individual's relationship to it. For example, during locomotion, the retina is considered to be moving through structured light, a conceptualization of stimulation quite different from the traditional notion of the retina as a receptive surface passively struck by light. Light emitted or reflected from environmental surfaces produces a stable optic array through which the eye moves along a path of locomotion and observation. Optical transformations result from self motion, and the activity of the visual system is hypothesized to be anchored to the variables of the optic array.

What are the implications of these assumptions for the empirical study of visual perception, and in particular, for an understanding of self-motion perception? First, priority is given to what is available in the light before an attempt is made to determine how the information is specified by the visual system. In most cases, there are several alternative sources of optical information specifying a self-motion event, and experiments must be designed to isolate the potentially informative variables so that their perceptual effectiveness can be assessed. Second, an attempt is made to account for what is perceived in terms of information intrinsic to the ongoing event, rather than in terms of information extrinsic to the event, e.g., interpretation based upon familiarity. Prior experience does play a role, but again the reciprocity between the perceiver and what there is to be perceived must be considered. An individual's ancestors' prior experience with evolutionary pressures may have resulted in the selection of "smart" visual system mechanisms (Runeson, 1977) which capitalize on a particular way of specifying a useful type of information. Such a mechanism would result in obligatory attention, since the individual would be sensitive to only one of several alternative optical variables specifying a critical event. Alternatively, an individual may be sensitive to several optical variables which may sometimes be redundant, but through prior experience the individual has learned that for particular situations one kind of information is more useful than other alternatives. Perceptual learning can occur in these cases where optional attention is possible. Either kind of selective attention can result in individual differences in sensitivity to optical variables.

Any translational motion of the eye can be scaled in arbitrary metrics (e.g., ft/sec, m/sec, mi/hr, knots) or in nonarbitrary metrics which are intrinsic to (i.e., derive their values from) the event perceived. Evolution of the visual system mechanisms which specify self motion must be constrained by the latter, since the former are inventions of man. If the metrics for self-motion information are intrinsic to the event, they must be found in the way light is structured by the layout and texturing of environmental surfaces and by the motion of the eye relative to those surfaces. We have isolated both self-scaled and environment-scaled metrics for the optical variables to which an individual

might be sensitive. (Arbitrary metrics are not optically available except under special circumstances where they coincide with self-scaled or environment-scaled metrics, e.g., flying at an altitude of 1 mi or flying over a ground surface delineated by 1-mi-square sections.)

An example of a self-scaled variable is self speed scaled in terms of the distance from the observer to the environmental surface. More specifically, locomotion over a ground surface can be scaled in <u>eyeheights</u> per second. This metric has an optical reality in that the mathematical description of the displacement over time of any optical discontinuity in any direction has a multiplier consisting of self speed divided by the eyeheight of the individual. This ratio will be considered an index of <u>global optical flow rate</u>. (For the optical locus directly below the eye, the local flow rate in radians per second is identical to the global flow rate in eyeheights per second.)

An example of an environment-scaled optical variable is self speed scaled in terms of the distances between the borders of adjacent ground-surface elements (e.g., fields) in the direction of travel. Thus <u>edge rate</u> can be defined optically as the number of optical margins (corresponding to ground edges) per second crossing the optical locus directly below the eye (Warren, Owen, & Hettinger, 1982).

Just as motion in any direction can be specified in meters per second, so can it be specified in eyeheights per second and ground units or edges per second. Since both eyeheight and ground-unit size can vary, to be useful, the nonarbitrary metrics must be carried by the optical variables specifying the self-motion event and the environmental surfaces. For example, descent rate scaled in eyeheights is equal to the fractional increase in global flow rate and the increase in perspectival "splay" angle which occur during approach to the ground surface (Owen, Warren, & Mangold, in press). Descent rate scaled in ground units is identical to the rate of decrease in global optical density (the number of ground units spanned by an eyeheight) as the ground is approached. Therefore, discovering which type of optical information an individual is sensitive to will indicate which nonarbitrary metric the visual system uses to scale self motion.

Factorial design is a standard way of assessing the effectiveness of multiple potential sources of information. A major difficulty in contrasting different optical variables as candidates for useful information, however, is the fact that they are often linked physically in ways that limit the number of degrees of freedom allowed in designing an experiment (see Warren & Owen, 1982). In cases of level or nap-of-the-earth self motion over ground units of regular or even stochastically regular size, for example, eyeheight and ground-unit scaling are linked. Optical flow rate and edge rate differ simply by a scale factor. The linkage between the two can be broken, however, by changing either altitude or ground-unit size during events. In two separate series of experiments, we have been exploring both alternatives.

A second difficulty is that when dealing with interrelated higher-order ratios, maintaining factorial control over one variable often means losing control over several other candidates. We have developed, within these constraints, several strategies for determining whether a potentially available source of information affects performance in ways which suggest that it is functionally effective information. The two lines of investigation described next exemplify our approach to determining the useful metrics for self-motion perception.

EXPERIMENTS

<u>Information and its metrics for the detection of loss in altitude</u>. The two experiments had two goals: (1) to test the perceptual effectiveness of two optical variables which vary with change in altitude, and (2) to contrast eyeheight-scaled with ground-texture-scaled specification of descent rate as perceptually effective metrics for optical self-motion information. Optical flow acceleration was eliminated on half the trials by slowing down on a linear path slope. Increase in perspectival "splay" was the only information for descent when horizontal texture edges and flow acceleration were eliminated. The utility of the two metrics had to be assessed in separate factorial crossings, since when eyeheight (z)-scaled descent rate ($\dot{z}$) is invariant ($\dot{z}_t/z_t = k$) throughout the event, ground-unit (g)-scaled descent rate ($\dot{z}/g$) is varying and vice versa. (A dot over a symbol indicates a derivative with respect to time. A subscript of zero indicates the value of a variable at the initiation of an event and t, the value at any time during an event.)

The 10-sec events represented either level or descending self motion over a flat ground surface covered with fields in four earth colors. The observer pressed one button for "level" a second for "descent."

In the first experiment, the fields had edges only parallel to the forward direction of travel (vertical-only texture), so that there was no information about forward velocity. As shown in Figure 1, greater fractional loss in

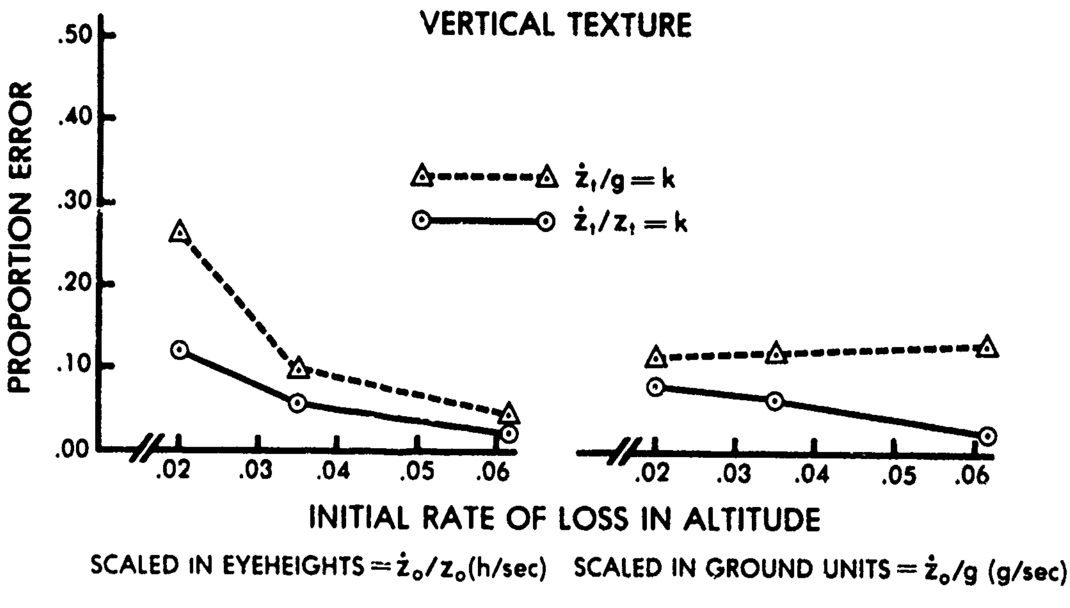

Figure 1. Proportion error for the three levels of initial rate of eyeheight- and ground-unit-scaled loss in altitude over vertical texture only, under conditions of constant optical flow rate ($\dot{z}_t/z_t = k$) and optical flow acceleration ($\dot{z}_t/g = k$).

altitude (i.e., descent rate scaled in eyeheights) resulted in lower error rates. In contrast, in the condition where rate of decrease in optical density (i.e., the rate of loss in altitude scaled in ground units) was constant throughout each event, error rates were the same over three levels of sink rate scaled in ground units (see the dashed line in the right-hand panel of Figure 1). The eyeheight metric accounted for 12.9% of the variance in error rate and 10.2% for reaction time, whereas the ground-unit metric accounted for only 0.8% of the variance in error rate and 0.2% in reaction time.

In the second experiment, square ground texture was used so that edges parallel to the horizon would manifest forward motion. Three levels of flow rate were included, and the proportional rates of loss in altitude were reduced to make the task more difficult. As shown in Figure 2, the results for descent

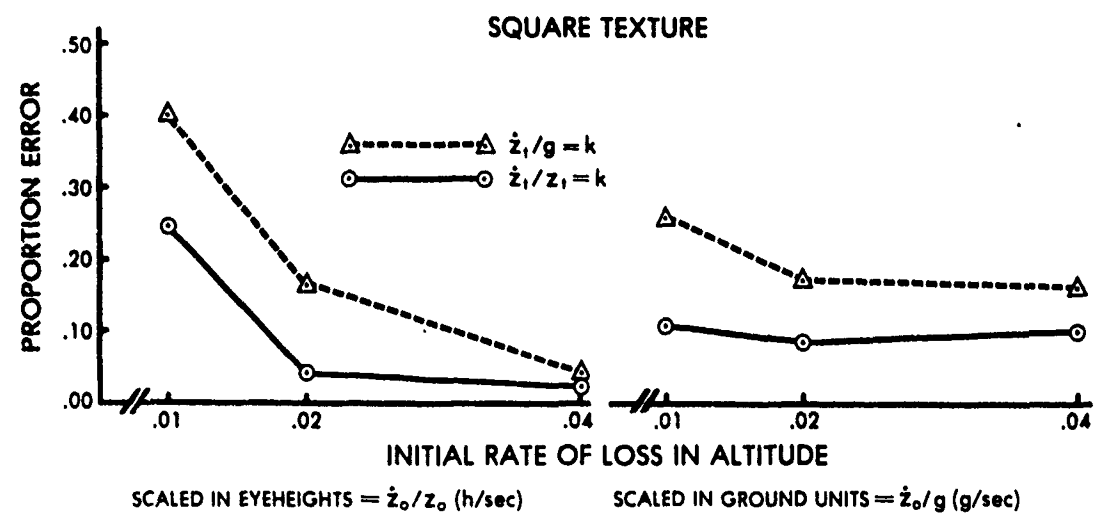

Figure 2. Proportion error for the three levels of initial rate of eyeheight- and ground-unit-scaled loss in altitude over square texture under conditions of constant optical flow rate ($\dot{z}_t/z_t = k$) and optical flow acceleration ($\dot{z}_t/g = k$).

rate scaled in eyeheights were essentially the same as in the first experiment except that error rates were higher, as expected, for the 1%/sec level of fractional loss. The pattern of results for descent rate scaled in ground units was, however, quite different. When decrease in optical density was constant ($\dot{z}_t/g = k$), the error rate was higher for the lowest level of ground-unit-scaled loss, then leveled off over the two highest levels (see the dashed line in the right-hand panel of Figure 2). When fractional loss was constant ($\dot{z}_t/z_t = k$), error rates were essentially the same over all levels of decrease in optical density ($\dot{z}/g$).

The eyeheight metric accounted for 12.0% of the variance in error rate and 14.2% for reaction time. The ground-unit metric accounted for only 0.5% of the error-rate variance, and 1.7% for reaction time. Increasing the level of global optical flow rate ($\dot{s}/z$, where $\dot{s}$ = path speed) increased both error rates and reaction times, accounting for 1.8% and 1.5% of the variance respectively.

It appears that having additional information about forward speed interferes with detection of descent. Also, observers were influenced more by ground-scaled information (manifested by decrease in optical density) when the relative rate of loss in altitude was constant and at a low level. Regardless, the results of both experiments indicated that the eyeheight metric was much more functionally pertinent in specifying loss in altitude than was the ground-unit metric.

It is of interest to note that at every level of fractional loss in both experiments, having optical flow acceleration available resulted in poorer performance than when optical flow and fractional loss were constant. This finding was unexpected, and suggests that the specifying mechanism can "track" the eyeheight-scaled information more accurately when it is invariant over an event than when it is exponentially increasing.

Information and its metrics for the detection of gain in speed. Global optical flow rate, i.e., the observer's speed ($\dot{x}$) scaled in eyeheights per second, varies with actual self speed and altitude, but is invariant with respect to the particular texture pattern on the ground surface. A flow pattern must also have a characteristic edge rate ($\dot{E}$), since optical discontinuities (inhomogeneities) are necessary to define the flow. Edge rate thus provides information for the observer's forward speed scaled in reference ground texture elements per second. It is invariant with change in altitude, but does vary with any change in the size of the ground texture elements.

It follows from the above analysis that flow rate and edge rate each differ from ground speed only by a scale factor and hence are linked to each other under the condition of constant altitude coupled with a regularly spaced terrain: if ground speed is constant, both flow rate and edge rate are constant. That two different sources of information are available in an optic array does not necessarily mean that they are perceptually effective, however. Both, either, or neither may be effective, and if both are useful their relative effectiveness need not be equal. In order to assess the separate perceptual effects of flow rate and edge rate, the normal linkage between them was broken in such a way that either rate could be held constant while the other accelerated.

The basic experimental design was a 2x2 orthogonal crossing of flow rate and edge rate where either may be constant or exponentially increasing. The desired combination was achieved by manipulating the ground speed and forward spacing of edge lines. (See Denton, 1980, for the influence of edge-rate acceleration on braking.) The basic task for observers was to view simulated self-motion events from each of the four basic types and to indicate whether the motion represented constant or accelerating speed. Event duration was manipulated to test the hypothesis that sensitivity to edge rate would be more affected by having more time to cross the necessary edges, whereas flow rate would be more instantaneously available and, therefore, less affected by additional time.

The results of three experiments indicated that fractional gain in flow rate ($r_{\dot{x}}$) and fractional gain in edge rate ($r_{\dot{E}}$) each have an effect on perception of increase in self speed, and that their effects are independent and additive. Figure 3 shows the results of the third experiment in a way which allows a

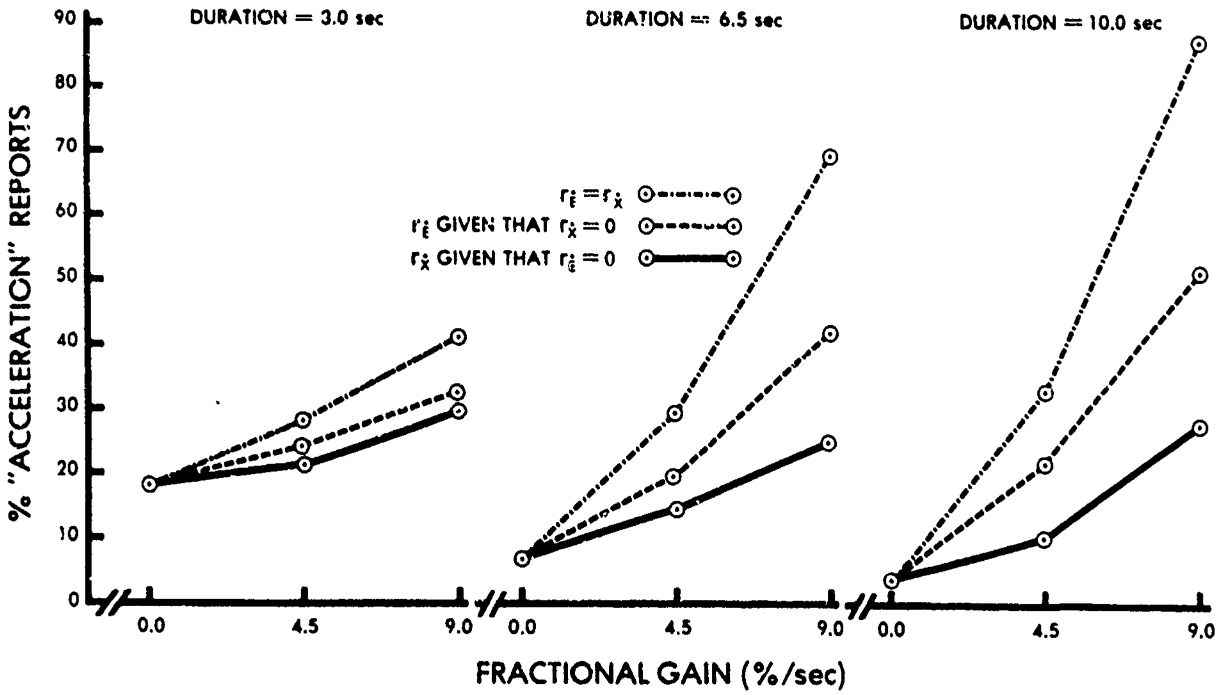

Figure 3. Percent reports of self-motion acceleration as a function of fractional gain and type of optical information.

comparison of the perceptual effectiveness of the two types of information. It is clear that when percent gain is the same, observers were much more sensitive to edge rate than to flow rate. The false-alarm rate for events representing constant speed ($r_{\dot{x}} = 0$) and regular texture ($r_{\dot{E}} = 0$) decreased with increase in event duration (compare the points at which the three lines originate in the three frames of Figure 3). This finding suggests that there is an illusory experience of acceleration when an ongoing event is first viewed. As predicted, the effectiveness of edge-rate gain increased with greater duration more than did the effectiveness of flow-rate gain (compare the steepness of the appropriate functions over the three panels of Figure 3).

It is of special interest to note that the functions in Figure 3 accelerate with greater gain, rather than showing the diminishing returns or approach to asymptote common in psychophysical experiments. Also of particular interest was the large range of individual differences, some observers being more flow-rate dependent some more edge-rate dependent. Since flow-rate sensitivity is veridical and edge-rate sensitivity is illusory, this difference may be useful in pilot evaluation and training.

DISCUSSION

It appears, then, that for detection of increase in speed during level motion, both self-scaled and environment-scaled sources of optical information are useful. In contrast, for the detection of loss in altitude, ground-unit-scaled information was not useful and may even interfere. It will, therefore, be interesting to determine whether eyeheight-scaled variables are the sole source of information for change in speed during loss in altitude. There is the possibility that sensitivity for the downward component may be to eyeheight-scaled variables and sensitivity for the forward component may be to ground-unit-scaled variables (i.e., edge or discontinuity rate). Edge rate has the interesting property of providing veridical ground-speed information when the ground-texture distribution is regular, but illusory information about speed when the spacing of ground elements increases or decreases. This fact may be a contributing factor in collisions with the ground during high-speed, low-level flight, especially for pilots who are more edge-rate sensitive.

The experiments described demonstrate that by a combination of controlling sources of optical variables within events and making factorial contrasts among events, the perceptually effective information for detecting change in self motion can be determined. Simultaneously, we can gain an understanding of how the visual system obtains nonarbitrary metrics for relative scaling of change from an event as it unfolds. As a result, we are now more knowledgeable about how to approach problems of speed, range, and altitude estimation (see Harker & Jones, 1980) and to determine what optical variables observers are adapting to during self motion (see Denton, 1976, 1977).

Our findings are also relevant to a criticism of the ecological approach to the study of perception, i.e., that it ignores or cannot deal with illusion or misperception. Our empirical approach to the separation of veridical and non-veridical influences on self-acceleration perception addresses the misperception issue directly. For whatever reasons (e.g., attention to edge-rate information which is useful in other situations, or simply having to do with the way the visual nervous system specifies optical change), the rate at which the eye traverses optical margins can be a source of misinformation about self motion when edge spacing is not regular. Both veridical and illusory perception of self speed are specific to, accounted for, and explained by variables and invariants in the optic array. Misperception is anchored to optic array variables in the same fashion as veridical perception, except inappropriately. Consequently, we have shown how sensitivity to misinformation can be studied in the same psychophysical framework as sensitivity to information which reliably and adequately specifies an event. Since misperception will lead to misguidance of locomotion, consideration of any self-motion illusion is of crucial importance, both theoretically and practically.

More detailed accounts of the experiments can be found in our technical reports (Owen, 1982, 1983, 1984). The isolation of global optical variables is described in a report by Warren (1982).

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AD-P004 334

SIMULATOR SICKNESS

SENSORIMOTOR DISTURBANCES INDUCED IN FLIGHT SIMULATORS

LAWRENCE H. FRANK
NAVAL TRAINING EQUIPMENT CENTER

ROBERT S. KENNEDY
ESSEX CORPORATION

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UNIVERSITY OF DAYTON RESEARCH INSTITUTE

ALVAH C. BITTNER
NAVAL BIODYNAMICS LABORATORY

SIMULATOR SICKNESS:
SENSORIMOTOR DISTURBANCES INDUCED IN FLIGHT SIMULATORS[1]

ABSTRACT

If sickness occurs in the simulator, but not in the real world, there is evidence of a bad simulation. We reviewed the available data on simulator sickness in terms of their incidence, etiology, and contributing factors. It was found that psychophysiological disturbances can occur during simulator flight, continue several hours post-flight, or be delayed. Effects were found in both motion-base and fixed-base simulators, to pilots, other aircrew, and instructors. Simulator sickness may lead to decreased simulator use, distrust of the training received, and post-effects which may place the individual at risk in real-life situations such as driving a car. Adaptation, while it is known to occur, is not the answer. Adaptation to the simulator can lead to acquisition of responses which may produce negative transfer to the aircraft. Data on the relative incidence of simulator sickness in various trainers, its symptomatology, possible etiology, possible solutions and suggestions for research are discussed.

INTRODUCTION

There have been numerous recent reports of aircrews experiencing psychophysiological disturbances, visual illusions and sickness following the use of flight simulators. Symptoms of simulator sickness have occurred not only during the simulator flight, but in some cases, have lasted up to several hours post-exposure. Furthermore, simulator aftereffects may be eight to ten hours post utilization (Kellogg, Castore & Coward, 1980). Incidents of simulator sickness have been reported in fighter (McGuinness, Bouwman & Forbes, 1981), patrol (Crosby & Kennedy, 1982) and helicopter simulators (Frank & Crosby, 1982). Interestingly, these occurrences have been reported in both motion-base and fixed-base simulators, to pilots, other aircrewmen, and to instructors.

Symptoms of simulator sickness include: disorientation, dizziness, nausea, emesis, spinning sensations, motor dyskinesia, flashbacks, visual dysfunction, burping, confusion, and drowsiness, among others.

The phenomenon of simulator sickness was first mentioned by that name in reports by Havron and Butler (1957) and Miller and Goodson (1958). Since that time, the evidence which has accumulated suggests that simulator sickness symptomatology resembles motion sickness and other forms of distress which occur following exposure to altered and rearranged sensory information, and perceptions. Hence, we feel that simulator sickness is a subclass of these phenomena.

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[1]The opinions expressed in this article are those of the authors, and do not necessarily reflect the view or the endorsement of the Navy Department.

REPORTED CASES OF SIMULATOR SICKNESS

As previously noted, the studies by Havron and Butler (1957) and Miller and Goodson (1958) were the first published reports of simulator sickness. They found a substantial incidence of symptoms among users of the Navy's 2-FH-2 helicopter simulator. (Instructor pilots were found to be more susceptible than students.)

In recent years, there has been an increase in the reports of simulator sickness, although the extent of the problem is still not clearly defined.

One of the first attempts to document the problem in the Air Force was reported recently by Kellogg, Castore and Coward (1980 and in press). They surveyed 48 pilots using the Air Force Simulator for Air-to-Air Combat (SAAC) and found that a majority (88%) had experienced some symptoms of simulator sickness (primarily nausea) during SAAC training. Of particular interest were the F-4 pilots, who reported delayed perceptual aftereffects occurring 8 to 10 hours following simulator flight. These included sensations of climbing and turning while watching TV, or experiencing an 180-degree inversion of the visual field while lying down. The authors cogently suggested that "the users of such (wide field-of-view) simulators should be aware that some adjustments may be required by pilots when stepping back into the real world from the computer-generated world."

In a study of flight simulator motion sickness conducted for the Canadian Department of National Defense, Money (1980) reported that nearly half of the pilots using the Aurora simulator experienced sickness ranging from slight discomfort to mild nausea.

An investigation of simulator sickness in the Navy's 2E6 Air Combat Maneuvering Simulator (ACMS) found that 27% of the aircrews using the ACMS reported varying degrees of symptoms (McGuinness, Bouwman & Forbes, 1981). The more experienced aircrews (over 1500 flight hours) had a higher incidence of symptoms than the less experienced flight crew. Dizziness was the most frequent symptom, followed by vertigo, disorientation, "leans," and nausea. The incidence of symptomatology was greater in pilots than in radar intercept officers (RIOs). The authors suggested that one reason for the reduced levels of simulator sickness found in the 2E6, relative to the Air Force SAAC, may have been the less intensive schedule of simulator time. Exposure duration and frequency appear to be potentially important variables, as has been found in other environments that produce motion sickness (McCauley & Kennedy, 1976).

Frank (1981) has reported that almost one out of every ten individuals using the F-14, 2F112 experienced symptoms of simulator sickness, and that close to 48% of the 21 aircrew sampled using the E-2C, 2F110 reported symptoms. Crosby and Kennedy (1982) have documented cases of simulator sickness in the P-3C, 2F87, particularly at the flight engineer's position. There have also been reported occurrences in the CH-46E, 2F117A (Frank & Crosby, 1982).

IMPLICATIONS OF SIMULATOR SICKNESS

The possible negative implications of simulator sickness can be grouped into three broad categories:

a. COMPROMISED TRAINING. First, symptomatology may interfere with and retard learning in the simulator through distraction. Secondly, since humans are flexible, trainees may adapt to unpleasant perceptual experiences. If new learned processes are not similar to responses required in flight, then the new responses comprise negative transfer to in-flight conditions.

b. DECREASED SIMULATOR USE. Because of the unpleasant side effects, simulators may not be used, or persons may lack confidence in the training that they receive in such simulators.

c. SIMULATOR AFTEREFFECTS. The exposure to the simulator may result in aftereffects, or post-effects. These are not unlike the post-effects of other motion devices; but their relevance to safety (e.g., driving home) is not known.

The consequences and practical significance of varying degrees of simulator sickness have been alluded to in the past. Crosby and Kennedy (1982) in a Navy study of the P-3C, 2F87 stated:

The cause(s) of these symptoms should be eliminated for the following reasons. The flight engineers are at risk when walking on the ladders at the exit of the simulator following training because of extreme unsteadiness induced by the simulator. The students become reluctant to take more training after this experience. Additionally, the symptoms of simulator sickness reduce the effectiveness of the flight engineers and hence jeopardize the flight crew in real flights that follow the training on the same day. Training is probably less effective because the flight being simulated. Scheduling problems due to illness result in lost crew time on the simulator following aborts.

Perhaps the most insidious symptom of simulator sickness is drowsiness. Drowsiness has been reported in connection with nearly all simulators which have reported simulator aftereffects. Drowsiness, of course, is a well known symptom of motion sickness; and the so-called sopite syndrome is likely to be the most debilitating problem of motion sickness, and may be of simulator sickness, also. Ryan, Scott and Browning (1978) report this after simulator exposures. It is acknowledged that the vestibular nuclei in the brain stem exert some control over the pontine reticular formation (Yules, Krebs & Gault, 1966). Reports from squadrons--particularly in Air Combat Maneuvering (ACM)--are that even brief exposures (i.e., less than one hour) result in long-term fatigue effects. Woodward and Nelson (1976) described the types of performance impairment most likely from sleep loss, including slower reaction time, short-term memory decrement, impairment in reasoning and complex decision-making, errors of omission, and lapses of attention. It is possible that the drowsiness that often accompanies vestibular and simulator sickness may have similar effects on human performance. Sleep loss has been shown to have a deleterious effect on vestibular processes. Dowd (1975) reported increased vestibular sensitivity, decreased recovery rate, and abnormal vestibular habituation to be associated with sleep deprivation. He warned of the implications of sleep loss for increasing the hazards of flying, due to degraded vestibular function.

ETIOLOGY OF SIMULATOR SICKNESS

It is extremely doubtful that there is a single causal factor for simulator sickness, any more than there is for motion sickness in general. Most of the distress and upset present in true motion sickness are also present in simulator sickness. Occasionally the symptomatology reported in connection with simulators

use does not involve nausea and vomiting, but includes headache, visual streaming and other more migraine-like symptoms. Careful perusal of the motion sickness literature reveals that these symptoms are also present occasionally in motion sickness experiences.

It is for these reasons that the cue conflict theory (also recognized as the sensory rearrangement theory) of motion sickness (Guedry, 1970; Reason, 1978; Steele, 1968) has been generally accepted as a working model for simulator sickness. In brief, the model postulates a referencing function in which motion information signaled by the retina, vestibular apparatus or proprioception may be in conflict with these inputs' "expected" values, based on a neural store which reflects past experience, or with how the system's circuitry is wired.

The problem with the model as presently pronounced, is that: a) there is no good method within the model to determine the magnitude of the conflict for specific combinations of "conflicts." b) Researchers have tended to address only conflict between sensory modalities. Guedry (1970) has suggested as an explanatory principle for space sickness that it is also possible to have a vestibular/vestibular conflict. We would argue that there can be further conflict between either one of the two visual systems (focal/ambient, Leibowitz & Post, 1982) and the vestibular information from either the canals or the otoliths, although conflict between ambient and the vestibular are expected to be the more motion sickness provocative. Additionally, it is logically possible that there could be cue conflict between the two visual systems. Whether conflict between the latter (e.g., forward motion [ambient perception] with receding depth [focal perception]) can produce emesis is problematic, although it is believed that the transformed perceptual events which would attend such a circumstance would challenge the plasticity capabilities of the CNS and might be the genesis of some of the more bizarre visual experiences which are occasionally reported.

It is apparent from our attempts to systematically evaluate the studies of simulator sickness--in terms of the etiological significance of design, personnel and scenario factors, etc.--that these pieces of critical information are not yet available. However, it is known that maximum motion sickness symptomatology occurs at a frequency resonance of about .2 Hz (McCauley & Kennedy, 1976; Money, 1970). Hence, it would appear advisable to avoid building simulators which resonate in this very low frequency range at the trainee's sitting position.

A case in point: Figure 1 presents a comparison between Military Standard 1472C (MIL-STD 1472C, 1981) vibration protection limits, projected envelopes for lesser symptomatology, and the SAAC frequency spectrum. The two solid lines are from MIL-STD 1472 and represent the 90% protection limits for an 8-hour vibration exposure. The solid U-shaped line, representing the exposure limit for below 1 Hz, is based on a criterion of frank emesis. The solid line, representing the exposure limit for above 1 Hz, is based upon a criterion of fatigue-decreased proficiency. The criteria for these two differ as a result of the large quantity of data generated on the effects of vibration on human performance above 1 Hz. In contrast, human performance data are currently insufficient to reach hard conclusions for exposures to very low frequency vibrations (i.e., below 1 Hz). The limits for below 1 Hz, then, should be viewed as conservative, since it can be predicted that decrements in performance can be expected to occur before emesis. Consequently, the heavy-dashed line represents our estimation of where 50% of the population will exhibit at least one symptom of simulator or motion sickness (e.g., pallor). The light-dashed line is our estimation of where at least one post-effect will occur. Note that the tolerance limits for each of

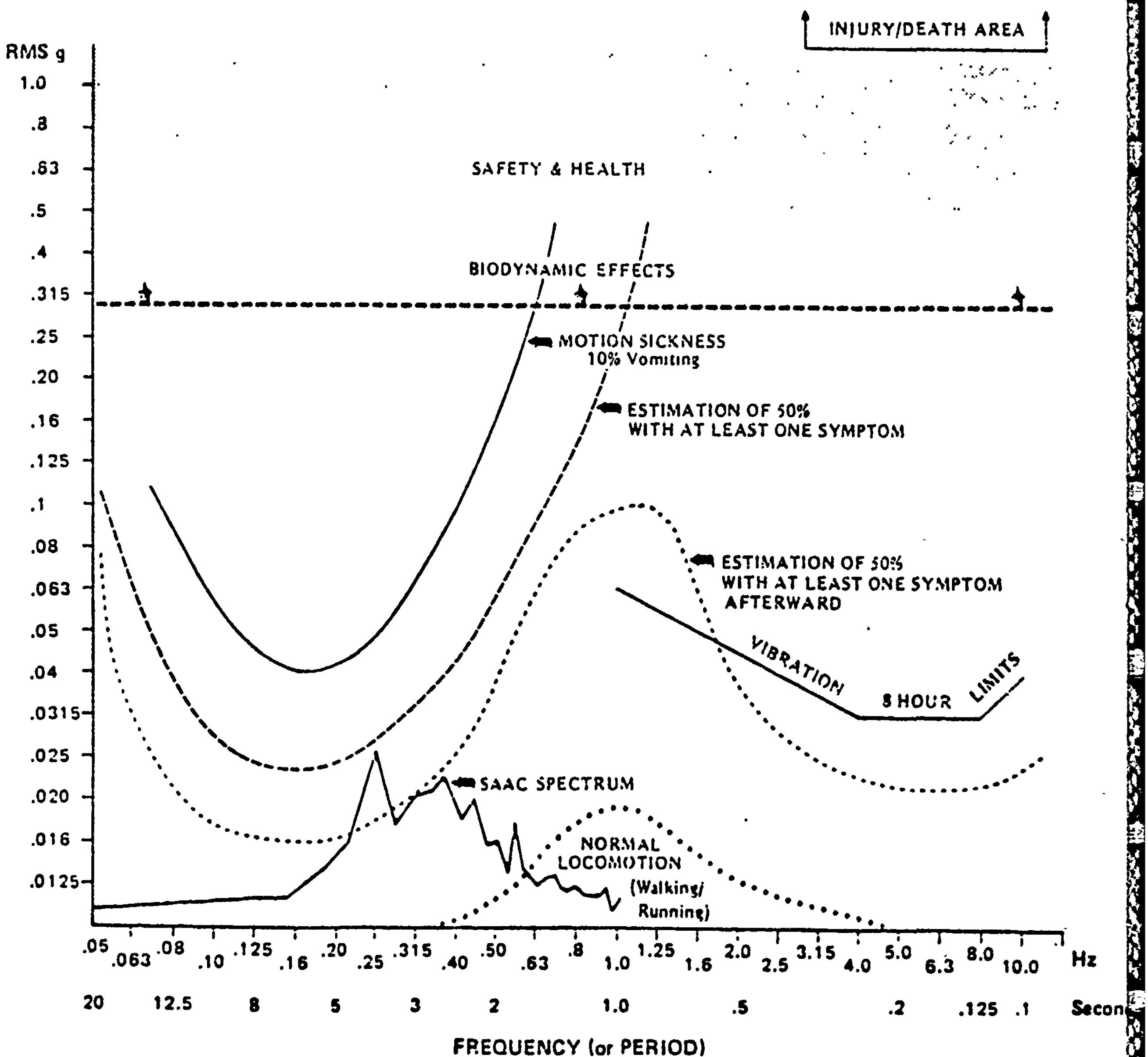

Figure 1. A Comparison Between MIL-STD 1472C Vomiting Criteria and a Projected Envelope for Lesser Symptomatology.

It is readily apparent from this figure that simulator resonant frequency is of critical saliency, relative to simulator sickness; and that simulators should be designed with these envelopes in mind.

these envelopes shift upward, coincident with the spectrum for normal locomotion. Note, also, that the lowest thresholds correspond to those energy regions most associated with motion sickness (c.f. Money, 1970).

The SAAC spectrum depicted in Figure 1 was replotted from Hartman and Hatsell (1976). This mapping reveals quite clearly that the resonant frequency of the SAAC inertial system intersects our estimated tolerance envelopes and, therefore, should be conducive to simulator sickness. Indeed, Hartman and Hatsell reported incidence rates for spatial disorientation, eye strain, tiredness, headache and nausea of 52%, 50%, 38%, 32% and 14%, respectively.

RECOMMENDATIONS

Although sparse information is available, there is a growing list of items that appear to work in alleviating the problem of distress in simulators. Each of these, listed below, has a consequent theoretical underpinning, which it is expected will stimulate research in order to determine the mechanism. The following advice is offered to simulator users to ameliorate the adverse symptoms of simulator sickness:

a. Eliminate unnecessary use of situational freeze. (The situational freeze buttom permits the simulator visual and inertial systems to be "frozen" in time by the instructor.) Although situational freeze provides a valuable tool for the instructor, freezing the aircrew in an off-horizon position can be very disorienting. Some aircrew have reported extreme difficulty in attempting to climb out of the cockpit at the end of a training session, if the visual (dome) display was frozen in a wings-down position (Frank, 1981).

b. Avoid indiscriminate use of the reset function. (The reset function permits the simulator instructor to reposition the aircraft to an earlier phase of flight after a situational freeze.) For example, an aircrewman may be practicing landings. Upon touchdown, the simulator can be frozen and "reset" to, say, 15 miles out. Unfortunately, when this occurs, 15 miles of visual information--in reverse--is also reset, and streams by the aircrew in a matter of a few milliseconds. This can be extremely disorienting.

c. Avoid prolonged and/or intense exposure to the simulator. The most bizarre and wide-spread occurrences of simulator sickness were reported in the SAAC (Kellogg, Castore & Coward, 1980), where 550 ACM engagements were flown over a five-day period.

d. Do not use simulators any more than necessary when suffering from the adverse effects of flu (flu shot?), hangover, etc., because in the literature on motion sickness and vomiting, these symptoms have been shown to summate (deWit, 1957; Cordts, 1982).

e. Remove scene content from the visual screen at the termination of the flight. This is an added safety precaution which may minimize any problems that might ensue when leaving the simulator.

f. Ascertain the visual and inertial lags inherent in current simulator and "tune" as necessary.

g. Ascertain simulator resonance (inertial and visual) and "tune" as necessary. It has long been known that maximum symptomatology of motion sickness occurs at a resonant frequency of .2 Hz (Money, 1970). Figure 1 shows that the "energy" from a SAAC flight tends to be in this region.

CONCLUSIONS

If sickness occurs in the simulator, but not in the real world, there is evidence of a bad simulation.

Simulator sickness can lead to: a) decreased use of the simulator due to motivational problems; b) distrust of training received in the simulator; and c) post-effects which can place the user at risk in real-life situations, such as driving home.

Adaptation is not the only answer, since adaptation can create its own problems--namely, adverse training. Due to the plasticity of the human nervous system, the user learns "bad habits" in the simulator which do not relate to later real-world requirements in the aircraft, and therefore constitute negative transfer.

The authors posit the following as chief candidates for research, since they are variables which appear to exacerbate the problem of simulator sickness: a) optical distortion; b) poor resolution; c) wide field-of-view; d) flicker; e) visual and inertial lags; f) viewing distance; g) head movements; h) subject's physical state; i) off-axis viewing; j) frequency and duration of exposures; k) scene content; l) motion frequency/acceleration spectrum; m) shudder; and n) visual-vestibular conflict.

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SESSION VIII

Applications

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Mr. Warren Richeson is the Deputy Chief of the Operations Training Division, AFHRL, Williams AFB, Arizona. He is currently assigned to the U.S. Senate Budget Committee as a senior analyst for the Space, Science and Technology function in the FY 1985 Federal Budget.

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ON-BOARD COMPUTER IMAGE GENERATOR (CIG) APPLICATIONS

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ON-BOARD COMPUTER IMAGE GENERATOR

(CIG) APPLICATIONS

ABSTRACT

Current training of military pilots fails to provide the complex visual environment associated with expected combat conditions. In addition, the training systems which provide the highest fidelity to combat are not available often enough to all pilots who require maintenance of volatile combat skills. On-board visual simulation using computer image generation is a technology which is ripe for exploitation for training. Training scenarios and development implications of on-board visual simulation are discussed.

INTRODUCTION

Three years ago Dr. Earl Alluisi closed the Image II Conference with some pertinent food for thought.[1] He described data on pilot attrition rates during war, which demonstrated that pilot/aircraft attrition rapidly decreased during the first few combat missions. The probability of the pilot being killed dropped from 40% on the first encounter to 1% on the fifteenth encounter for one group and from 20% on the first encounter to 2% on the tenth encounter for another group. At least some of the initial high attrition rate can be attributed to the pilot's lack of sufficient and frequent exposure to a high threat, combat environment during his training. Existing training is limited in its capability to provide this environment in both range training exercises and ground based simulators.

Some of the deficiencies of range training exercises are:

a. Range Availability

Limitations on resources such as range real estate and aggressor role playing aircraft result in pilot exposure which is too infrequent to maintain skill proficiency at a high combat level. Squadrons deployed at sea often have no ranges available for tactical exercises for long periods of time.

b. Range Fidelity

Ranges are often in geographic areas not representative of those expected in combat. Urban area scenarios or intelligent, mobile ground targets/threats are essentially non-existent.

c. Range Complexity

Ranges do not have the capability to provide the number of targets/threats expected in the modern battlefield. Capability to provide dirty battlefield conditions is limited.

d. Performance Limitations

For reasons of pilot/aircraft safety, range training exercises restrict allowed performance to be well within expected combat performance envelope. For example, minimum altitude might be 200 feet during training when minimum altitude in combat is expected to be 50 feet.

e. Live Fire Restrictions

The cost, logistics, and safety considerations limit live fire practice in weapons delivery exercises. Exercises involving live fire of expensive, guided munitions, such as Maverick are almost non-existent.

f. Instruction Feedback

Logistics and communication problems associated with range training often dictate a lack of capability to instruct a pilot to correct his errors during the exercise. Capability to allow repetitions of scenarios which address deficiencies of individual pilots is almost non-existent. Emergency procedure training is minimal.

Although many of these deficiencies can be overcome in ground based simulators, they also have deficiencies in providing the high threat, combat environment.

a. Simulator Availability

The cost of ground based simulators with full visual simulation systems is too high to allow fielding in the quantities required for frequent use by large numbers of pilots to enhance and maintain combat skill proficiency. Current technology results in simulators being too large, complex, and delicate to allow fielding with deployed squadrons.

b. Simulator Fidelity

Existing visual simulation technology doesn't provide the visual environment complexity associated with the battlefield.

ON-BOARD VISUAL SIMULATION

In an effort to overcome some of the training deficiencies noted above and provide pilots with training in an environment which more closely resembles the high threat combat environment, the Naval Training Equipment Center has initiated an exploratory development effort with the objective of demonstrating feasibility of improving training through the use of on-board aircraft visual simulation. As part of this effort, a contract with DCS Corporation was awarded in August 1983. The objectives of the contract were: to survey and analyze Navy aircraft avionics displays, graphics generators, and computer resources for potential application to on-board visual simulation; to survey and analyze pilot training deficiencies which could be effectively addressed using on-board visual simulation, and to provide a video tape of simulated training scenarios which could be evaluated by users.

As of this writing no selection of a proposed implementation of on-board visual simulation has been made. Several candidate implementations have been identified. These are described together with development implications below:

SOFTWARE CHANGES TO EXISTING AVIONICS

The Air Force Integrated Flight/Fire Control (IFFC) program[2,3] has already demonstrated the capability of the IFFC system to perform an on-board simulation (OBS) function for pilot training in air-to-air gunnery, air-to-ground gunnery, and bombing. In the Air-to-Air OBS mode, the pilot can select one of ten canned target maneuvers. The OBS then generates a target aircraft symbol on the aircraft Head-Up-Display (HUD) which allows the pilot to judge direction, range, and aspect of the target. When the pilot dry fires his guns, the OBS system provides immediate scoring data. This scoring data when combined with HUD video tapes allows effective assessment of pilot performance in post-flight debriefs. Thus Air-to-Air Gunnery can be trained without a cooperative target aircraft and without live fire. An additional benefit of the IFFC-OBS training is that nose-to-nose encounters are possible. Even in dry fire training with a cooperative target, nose-to-nose encounters are currently forbidden for safety reasons.

In the Air-to-Ground Gunnery and Bombing Modes the Pilot can also select from a variety (ten each mode) of target types. The OBS then generates a target symbol which the pilot can view on his HUD. A dry fire weapon release can then be scored. Since the ground target can be positioned anywhere in the three-dimensional space surrounding the aircraft, it is possible to simulate a synthetic ground level at a high actual altitude. Thus air-to-ground gunnery and bombing can be practiced at a high, safe altitude.

Since all three OBS modes are available to the pilot, air-to-air and air-to-ground can be exercised on a single flight, thereby allowing more training in less time. Since the pilot has control over the tactical scenario he can concentrate on those scenarios which he considers most difficult or in which he needs to improve his performance.

Although the Air Force IFFC-OBS system has demonstrated the capability of on-board avionics to serve a training function, additional research and development is required if the full potential of on-board simulation is to be realized. Some of the issues which must be addressed are:

a. To what extent can the IFFC-OBS system concept be implemented on other aircraft computer/display systems?

b. Can capabilities for simulating multiple, mobile targets/threats be incorporated into existing aircraft computer/display systems with relatively low cost software modifications?

c. Can targets/threats be "intelligent?" Can they be made to react to pilot maneuvers?

d. Given the computational load limitations of aircraft computers, what is the best mix of training scenario and level of difficulty?

e. Can on-board simulation capability be incorporated into new avionics at the design stage?

Due to the extensive test, evaluation, and approval procedure required prior to any modifications of software load on operational aircraft, the above issues would initially be addressed via emulation on a ground based simulator such as the Visual Technology Research Simulator (VTRS) at NAVTRAEQUIPCEN. Following development and evaluation at VTRS, the next step would be a test and evaluation using a facility such as the Tactical Avionics and Software Test and Evaluation Facility (TASTEF) at the Naval Air Test Center followed by airborne evaluation.

HARDWARE ADDITIONS TO EXISTING AIRCRAFT

Although software modifications offer significant potential for enhancing training and combat readiness, it is unlikely that the computational capacity of aircraft computers designed for operational needs will be great enough to provide simulation of a complex combat environment. In order to go beyond the simulation capabilities of such equipment, hardware designed as a training package could be added to an aircraft for use during training exercises.

The Tactical Aircrew Combat Training System[4] (TACTS) (originally called Air Combat Maneuvering Range or ACMR) demonstrated the feasibility of using an add-on training pod to operational aircraft. The TACTS system is a computer-based data communication and tracking network that provides range training officers and observers on the ground with real time information on the flight dynamics, weapon system status, and weapon firing of each aircraft engaged in a training mission.

Although the TACTS system demonstrates the concept of employing an aircraft mounted pod for training, the objective of the system is to allow performance assessment and post-flight debrief. The concept of on-board simulation to allow independent pilot engagement of synthetic targets is not addressed by TACTS. The TACTS system success has led to incorporation of the pod functions into the internal structure of the F-18. An evolution from strap-on training modules to incorporation into aircraft systems is an obvious path for on-board simulation to follow.

With the addition of computation power afforded by a strap-on pod it becomes possible to extend the image generation/display capability from simple symbolic imagery to the complex imagery associated with high threat combat environments. The state-of-the-art of computer image generation (CIG) has advanced to the point where an on-board CIG can be developed with the capacity to provide simulated terrain imagery, sensor imagery, or high detail targets.

Another area which could benefit from training specific hardware modifications is displays. Current Navy aircraft cockpits utilize HUD's and panel displays. Both of these have relatively small fields of view in directions which are fixed to the cockpit. This results in limiting the potential training scenarios no matter what CIG capability is available. Large fields of view are required for all aspect air combat, near hover, nap-of-the-earth flight, navigation, ground attack on targets of opportunity, and steep turns in low

level flight.[5] The use of Helmet Mounted Displays (HMD) such as the Integrated Helmet and Display Sighting System (IHADSS)[6] on some current and planned aircraft offers a display in which a relatively small field of view is slaved to the pilot's head pointing direction. A display of this type would be adequate for the training tasks which require a large field of view but do not require peripheral vision. The implementation of HMD for on-board simulation could be a relatively simple task if the HMD were already existing in the aircraft. A more involved, though certainly feasible development, would utilize a training specific HMD which is installed just for training exercises, on aircraft which do not have an HMD.

Some training scenarios which could be implemented with an on-board CIG and an HMD (if necessary) are:

a. Low level flight over terrain while at sea or at a high, safe altitude.

b. Ground attack on synthetic high detail content, intelligent, mobile targets in synthetic or real world terrain environments. Increased CIG scene detail content would allow practice and training in the target acquisition, recognition, and identification tasks of the mission.

c. Landing on synthetic flight decks under simulated adverse weather/high sea state conditions while at high actual altitude.

d. Dry fire of expensive guided munitions against synthetic, high detail targets.

The use of a ground based simulator to develop and evaluate CIG or display on-board visual simulation hardware strap-ons, as in the software modification case, is the logical approach to developing the optimum training system. Some of the additional research issues which would be addressed include:

a. Develop and demonstrate training potential of on-board simulation training scenarios for user evaluation.

b. Perform trade-off analyses of on-board simulation resource requirements vs. training need.

c. Develop and test on-board simulator hardware prior to transition to aircraft.

OTHER ON-BOARD APPLICATIONS

The use of on-board visual simulation concepts is not limited to the training of pilots of airborne platforms. It is not difficult to conceive a wide variety of training scenarios which are feasible for other aircrew or other platforms. For example:

a. Periscope view simulation on-board submarines while submerged at sea below periscope depth.

b. Sensor display simulation of harbors, confined channels, and landmasses for ships at sea.

c. Sensor display of simulated adversaries in combat scenarios while at sea.

The development of on-board simulation technology would allow presentation of non-real world imagery for training purposes.[7,8] A variety of concepts in aircrew training technology have been demonstrated to enhance training without attempting to replicate real world visual environments. The use of relatively simple symbology to represent command flight paths, weapon effectiveness envelopes, and energy/maneuverability diagrams, for example, would probably be within the capability of on-board computer systems.

SUMMARY

The development of increased computer capacity and sophisticated displays in modern aircraft offers a new opportunity for the simulation community to enhance the readiness of the military for combat. The potential for on-board simulation to allow training and maintenance of combat skills when ground based simulators, instrumented ranges, or role-playing adversary aircraft are not available is enormous. The logical approach to developing and implementing on-board simulation concepts is to utilize ground based simulators.

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CIG GOES TO WAR:

THE TACTICAL ILLUSION

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ABSTRACT

In a real shooting war, the tactical pilot learning curve is both steep and expensive. The ability of one side to learn the lessons of aerial combat just a little bit faster than the other may ultimately decide the outcome. Simulation can play a decisive role in preparing pilots to survive and prevail in such a situation; however, realistic simulation of a complex multi-threat tactical environment has remained an elusive goal of computer generated imagery. Current systems have been unable to present both the quantity and quality of visual cues required to train effectively in all phases of the tactical combat experience.

Recent advances in CIG technology~~, at Rediffusion Simulation and Evans and Sutherland~~ have created a system which reaches new levels of realism and effectiveness in such a task. The CT5A system can provide a dense, navigationally specific terrain model of large geographic extent, while providing a substantial reserve of processing capability which can be used to present a rich dynamic environment. Within this environment a number of ground and airborne tactical threats can be simultaneously active. Unique features within the CT5A system allow the orchestration of complex tactical effects such as missles, cannon, tracers, flak and bomb impacts. Special modeling, shading and coloration strategies allow the presentation of very high fidelity aircraft models to support midair refueling, formation flight and target acquisition/recognition. Many dynamic scene elements can be simultaneously active in both independant and chained motions, with proper occulting and realistic behaviour maintained. We will discuss the various features of the CT5A system which make such simulations possible, and will present dynamic visual examples of these and other tactical scenarios.

INTRODUCTION

The weapons of war have increased tremendously in both their effectiveness and sophistication. The microelectronic revolution has brought to the battle front a new host of devices which are extremely effective at detecting, identifying and destroying a would be intruder. Some of these can 'see' in the dark, over the horizon, and through the electronic fog of jamming devices. Air battles are now fought at ranges where the combatants may never even see each other, and the first indication of an attack may also be the fatal strike. In this kind of tactical environment it is often the subtle advantages gained by prior experience that allow a pilot to survive. This fact has been verified in numerous historical engagements, and the actual statistics show that a pilots chance of survival rises rapidly and appreciably as he gains actual combat experience. A pilot who survives fifteen tactical engagements may decrease his subsequent probability of being killed by a factor of ten[1]. His effectiveness at meeting tactical and strategic goals during a mission is also dramatically increased.

These facts present a powerful argument for providing simulator training of the most thorough and effective kind. As the burden of gaining experience is shifted into the simulator; expenditures of men, aircraft, fuel and ordnance are conserved, and the long term effectiveness of these resources in an actual hot war is enhanced and ensured. The ability to field an already experienced and 'savvy' tactical force is in itself a deterrent to a would be agressor, and thus advances the global objective of preserving peace through strength and preparation.

THE CIG CONTRIBUTION

Over the last twenty years, and primarily during the last ten years, computer image generation (CIG) has helped provide a critical facet of the pilot training experience. A first step up from the instrument only simulators was the use of a computer to generate a ground plane and horizon line. This allowed the pilot to use, for the first time, 'out of the window' visual cues to understand and control his aircraft flight dynamics.

The importance of this accomplishment cannot be overstated. It allowed the man in the cockpit to function in the same integrated fashion that he does in the real airplane, with his major focus of attention outside the cockpit.

As image generation (IG) capacities increased it became possible to provide a 'realistic' and 'rich' enough environment to train pilots in takeoff and landing. This particular training task has major value for the commercial airlines, and a great deal of effort has been put into optimizing CIG systems and simulators for this type of training. The orchestration of weather related special effects and other special capabilities has resulted in FAA approval to conduct aircraft type-transition training entirely within the simulator, with only a check ride in the actual aircraft before commencing commercial flying.

The military has benefited significantly from this technology, and has provided driving inputs based on its own needs. Today this type of simulator training is regularly used to provide a pilot his initial introduction into a new aircraft type.

The CIG has always had a significant advantage over TV camera and model systems in providing realistic dynamics and special effects. Even though the realism of an actual miniature model cannot currently be matched with CIG, the ability to stage unconstrained motion, complex weather effects, and multiple interacting dynamic models has given it the edge for tactical fighter training. A new generation of air-to-air tactical simulators is now entering service which allows two pilots to fly against each other through the medium of the simulator. In such a system, the image of one aircraft is portrayed in the simulated environment of the other, and vice versa. The tactical maneuvers of each pilot determine not only the appearance of the environment to himself, but the behavior of his aircraft as seen by his opponent. With such a system a great deal of very realistic combat experience can be gained and the price of failure is measured in wounded egos rather than demolished aircraft.

Not until very recently did CIG simulation systems attempt to address the special problem of tactical flight at very low altitudes. This type of flying is a direct response to the growing need of military aircraft to totally avoid detection during the approach phase of a strategic strike. It typically involves flight at high subsonic speeds and at altitudes as low as the pilot can tolerate. A variation employed by rotorcraft involves literally hiding in the 'nap' of the earth, with the

skids occasionally less than six feet above the ground. In all of these situations the success of the strategy is directly related to how well the pilot keeps his craft 'hidden' from the biological and electronic eyes of the enemy. Unfortunately, this type of flying may simply substitute the terrain as the main enemy. The high risk of impact with the terrain is borne out by the statistics associated with training for low level flight.

Simulators have, thus far, been very ineffective in providing training for this flight regime. Until recently, CIG systems have been unable to present both the quantity and geographic density of visual cues required to convey to the pilot an unambiguous sense of where the terrain is. Indeed, recent studies done on older CIG equipment have suggested that the cueing levels needed cannot be achieved well enough to convey an accurrate sense of absolute spatial relationships[2]. This is rapidly changing as much more sophisticated CIG equipment takes to the field.

The 'strike/fighter' mission combines the hard parts of all of the above problems. A typical mission scenario calls for ingress at tree top level, threat detection and avoidance, delivery of ordnance with rapid damage assessment, and egress at maximum speed with probable engagement by opposing aircraft. The effective simulation of such a mission requires attention to a variety of details. The terrain model must be visually realistic, navigationally specific, and optically dense. A realistic number and distribution of enemy ground based threats must be integrated into the terrain, and their defensive response properly controlled and portrayed to the student pilot. Strategic targets and targets of opportunity must be modeled and situated to provide realistic problems in target acquisition, identification and demolition. A sufficient reserve of CIG capacity must be used to allow the introduction of multiple friendly or enemy aircraft, a refueling tanker or detailed formation wing man. In addition, the weapon bursts, flak, missle plumes, bomb impacts and lead ship must have believable and accurate dynamic representations.

The effective achievement of this totally simulated environment relies on specifically designed IG hardware, powerful data base development techniques, and innovative responses by the real time software. A brief overview of the CT5A system will highlight some of these features.

CT5A OVERVIEW

The CT5A image generator is an enhanced version of our fifth generation CIG system. It incorporates features which represent a great deal of acquired expertise in the overall simulation field. The system is comprised of four basic system units which can be configured in various quantities to provide the capacity, resolution and viewing windows required for a variety of specific tasks. This flexibility and modularity is achieved without any appreciable penalty in overall performance, and each unit coordinates with the others to provide maximum overall throughput.

The Object Manager (OM)

The OM accomplishes several important functions for the system. It serves as a Viewpoint Processor, performing tasks with are channel independent but common to a single pilot eyepoint. One of these tasks is called paging, which is the process of obtaining data base information blocks from the disk for use by the IG. Paging occurs entirely within the OM hardware, but is implemented as a background task since demands for new disk blocks are comparatively infrequent.

The pager identifies blocks which will shortly be needed, discards blocks which are no longer needed, and performs all block mapping and 'garbage collection' incumbent with these tasks. It can provide a continuous stream of data into the IG at very high rates, and thus supports rapid flight over very dense data base regions.

The OM also performs, for each display field, the operations necessary to cull the data base to the minimally required subset and presents these portions to the rest of the system in a front to back visual priority order. Its culling operations include level of detail (LOD) selection and field of view (FOV) rejection. The displayed image uses only the simplest version of each scene element required for the particular viewing distance.

These operations are controlled by parameters which can be changed by the real time program in response to load levels at various places within the IG. These parameters are manipulated to ensure that the amount of displayed detail is at or near maximum all the time. The data base management processes within the OM utilize a hierarchical data base tree structure which allows very large data bases to be processed very rapidly, and essentially decouples the processing time from the overall data base content[3].

The complex chaining and control of dynamic coordinate systems is accomplished within the OM. It builds composite transformation matrices from the Euler angles supplied by the real time system, and chains translational and rotational degrees of freedom as specified by the model developers and the Host program. It also implements a complex and flexible mechanism for switching sub-parts of models in or out of the scene based on real time controllable select switches.

The Polygon Manager (PM)

The PM assembles and outputs polygons and light strings as indicated by the Object Manager. It can serve up to eight display channels, and is responsible for routing scene information to the channels which require any particular scene detail. It performs further culling tests to eliminate back faced polygons and polygons which will be too small when displayed, as well as polygons which are wholly off screen in any display window. The perspective area test threshold is controlled by the real time system to further control dynamic load and ensure operation at maximum scene content levels.

The PM performs calculations to simulate the illumination effect of the sun on surfaces. This operation employs a complex illumination model which simulates the directional nature of sun illumination, provides for back surface illumination with some retained sense of curvature, and allows one of two selectable functions which portray bright sunlight or overcast cloud type illumination. The sun is characterized by a direction vector which can be controlled in real time. The absolute level of illumination is later determined by a multiplier factor representing the intensity of the sun, and allows complete gradual control of illumination effects.

The Geometric Processor (GP)

Each display channel will generally have one GP in it, although variations have been delivered where a single GP feeds two display channels. The GP performs the actual translation and rotation of the data base elements into final displayed coordinates for a specific channel. This transformation includes the particular aim direction of the channel (including rotation and FOV), as well as the scaling

required for the final display format (i.e. display lines and elements). It performs the windowing operation to clip off portions of the scene which are off screen, and does the depth divide to convert the image into perspective coordinates. During these operations the intensity and depth information is properly maintained so that correct shading and fogging can be done later.

The GP also implements a general approach to processing light strings. Both straight and curved strings are supported, and complex directionality is provided. A variety of flash patterns are provided, and VASI and strobe simulations are functionally accurate. The light build-up problem associated with light strings is solved here as well, and the resultant displayed lights have the maximum resolution and quality possible in a raster scan display system.

The Display Processor (DP)

The DP converts the GP's vertex based description of the image into a matrix of individual picture elements (pixels). Along the way it removes portions of the scene which are hidden behind other scene details, performs the final shading calculations, and applies the effects of the fog function to the image. The scan conversion process employs special anti-aliasing algorithms to avoid the 'stair stepping' and scintillation that was so obvious in early systems. The apparent resolution of the final picture is very high, and scene details are able to move smoothly and subtly through the picture matrix in a natural way. The DP treats light points with special algorithms to preserve proper behavior with distance, and allows point lights to 'burn through' the fog at greater ranges than adjacent surfaces.

From one to four DPs can be connected to a single GP, depending on how much resolution is required in the final display. The DP can support a wide variety of custom display formats, including 1000 line resolution and some non-interlace cases. The DP generally is used to provide full color imagery, but can be configured to provide monochrome pictures, and has been delivered in configurations where a single DP handles two monochrome display channels.

SPECIAL SYSTEM FEATURES

The CT5A image generation system includes many state of the art features which enhance the realism of a simulation without reducing the total quantity of scene detail available. These features are provided by various combinations of special purpose hardware, firmware, and real time software, and may be combined to produce a visual scene that gives a high density of visual and tactical cues while providing a very realistic simulated environment.

Surface Shading

Surfaces in the visual environment may be shaded in a variety of ways. Flat shading is the most prevalent, and is used to depict most planar surfaces in the data base. A flat shaded surface has a constant overall intensity which is determined by the orientation of the surface with respect to an imaginary (and user controllable) sun. This method is used for buildings, roads and most planimetric cultural features.

Smooth shading is used when the modeler wants to provide the visual impression of a continuous curved surface, such as the hull of the F-15 in Figure 1. An intensity is computed independently for each corner of a polygon, based on the approximate surface orientation at that corner. This orientation will generally be

calculated by the data base compiler to be the same for each surface which uses this corner. The visual result is that the sharp line which would otherwise mark the edge between the two surfaces is made to disappear. The intensity inside the surface is averaged from edge to edge to give the illusion of a true curved surface. The modeler can exclude some edges from this process, creating the impression of a crease or sharp bend in the surface.

Fixed shading allows the modeler to specify the displayed intensity of each corner of a polygon independently of the sun direction. This method can be used to apply weathering effects or smudges on a surface, such as the runway smudge marks shown in Figure 2. By setting the perimeter intensities of a surface to match the concrete and by setting the interior intensities darker, the impression of soft edged or fuzzy patches is created.

Color blending may be used on data base surfaces, and causes the color, rather than the intensity, to vary smoothly from one edge to another. This is typically used with fixed shading, but may be employed with any of the other shading modes, and is particularly useful in providing the gradual changes in color found in fields, forests and bodies of water, as shown in Figure 2.

Surfaces may also be specified as non-occulting. This causes the system to add the color of the non-occulting surface to the surfaces beyond. This allows one surface to seem to fade into another, and is extremely effective in producing the visual effects of luminescent details such as the afterburner plumes in Figure 1. It is also used to provide soft edges to aircraft camoflage, flame effects, clouds, sunset glow in the dusk horizon, and the visual representation of the sun. This last application is unique, and provides the proper visual effect of an opposing aircraft 'hiding' in the glare of the sun.

Transparent surfaces are provided in the CT5A system. This is achieved in the Display Processor by having the transparent surface partially overwritten by subsequent surfaces which lie beyond. This method is useful for all surfaces that would appear to be glass or partially transparent like chain link fences. Note the transparent canopy in the F-15 of Figure 1. Transparent surfaces have also been used with great success in portraying the shadow of a low flying aircraft. Such a shadow can be 'flown' over the ground in a position which tracks the aircraft, and will appear to partially darken everything it passes over. While this effect is not totally correct in the general sense, it does provide proper visual behavior as seen by the pilot, and is a very valuable cue in judging altitude.

A quite different use of transparency is in helping to hide the change when one scene element is replaced by another (more or less complex) version. As this replacement is taking place the retiring version is made more and more transparent while the replacement version gets more opaque. Because this makes the switches much less noticable, the transition ranges for scene elements can be significantly shortened. This allows more detail to be put into the nearby scene, thus giving a higher scene complexity. The very high density of trees and shrubs shown in Figure 3 is achieved this way.

A feature of the DP is the ability to display landing light effects and landing light lobe patterns. This is a separate function in the DP apart from the regular illumination of the scene, and provides the effect of own aircraft landing lights on the runway and surrounding surfaces as the pilot approaches touchdown. The illumination due to landing lights falls off with distance from the eye, and the lobe is an optional shape which can be further applied to this illumination. A variety of lobe patterns is simultaneously available, and custom patterns are routinely

provided. The modeler can indicate whether or not he wants certain surfaces to be affected by landing lights.

Dynamic Models

The CT5A system provides a total of 32 dynamic coordinate systems which can be simultaneously active in the simulation. At run time, one of up to 128 different models can be associated with each coordinate system. An example is a data base that has five coordinate systems which will be used for aircraft. The selects of each coordinate system are set for the particular aircraft type desired. This allows the instructor, for example, to specify at run time which types of other aircraft will be doing what. It provides the flexibility to display five aircraft of the same type, but each with independant motion, or five different aircraft, or any mix, without committing permanently to any one combination when the data base is first built.

Coordinate systems can have up to six degrees of freedom, and can be chained together so that each coordinate system acts in the frame of reference set up by the preceeding coordinate system. For example, the flaps on an airplane need to remain attached to and follow the aircraft motion, but are required to exhibit an independent rotation about their hinge axes. Other examples include landing gear and speed brakes. The chaining can be set up by the real time system, or built into the model by the data base designer.

Proper visual priority between dynamic models is maintained by range sorting. This process produces visually correct results as long as any pair of models remain separated by at least their combined radii. This sorting process can even include parts of the fixed terrain environment, and provides proper visual occulting in complex tactical scenarios such as tanks hidden in a forest.

CT5A provides a method of animation called model cycling. In cycling, the model selects are sequenced in real time at controllable rates. An example is the various stages of an explosion. The various visual representations are created as a sequence of models, each on the same coordinate system but with a different model select. The IG may then sequentially cycle through the selects to provide an animated explosion that can be placed anywhere in the data base. Sequences can be chained together, so that one begins when another finishes. This can be used to provide a very realistic representation of a missle hit, followed by trailing smoke, ending in an explosion, for example.

Weather Effects

A variety of realistic weather related effects is possible with the system. The most basic effect is simple fog, which is provided by the DP hardware and can be set at any 'depth' or visibility range from zero to 80 miles. The depth and color of the fog can be controlled in real time, and modulation of these values produces a dynamic 'scud' effect. Similar strategies are used to simulate lightning and the flash of own ship's rotating beacon.

An actual cloud model can be created to provide a sense of depth and texture while flying over an overcast, and scud effects provide realistic entry and exit from the cloud layer. The real time system can control the altitude of the cloud top and bottom, and orchestrates the overall illumination level, fog range and color to give the proper impression when above or below the overcast.

The real time system controls the basic illumination of the scene in a continuous

spectrum from bright day to dark night. Correlated effects, like the gradual emergence of cultural point lights as dusk approaches and the reddening of the western horizon are provided. Two shading calculations are provided to simulate the very directional illumination of a clear day or the diffuse non-directional illumination of an overcast day. The comprehensive treatment of weather and environmental effects allows the system to inject a very believable adverse weather facet into the training exercise.

Special Options

Two optional features of the system provide important feedback to the pilot for critical tasks involving low level flight or maneuvering in confined areas. The system is capable of detecting collisions of parts of own ship with terrain features and 3D structures. The collision detection process uses a special part of the data base management tree to determine if a test point is inside a volume of space identified as a collideable solid object. These objects might include buildings and other structures around an airbase, the trees and vehicles in a confined area landing site, or tall radio towers throughout the data base.

A related capability is height above terrain determination. The data base tree structure is traced to identify the terrain area immediately below the test point and return the equation of the terrain surface at that point. The host computer can then compute the actual height of the aircraft above the terrain, and use these inputs to support terrain following and terrain avoidance missions. The test point need not be a part of own ship, and a sequence of points spread out in front of the aircraft can be used to provide terrain look ahead.

MODELING STRATEGIES

When a pilot straps himself into the simulator, he's not thinking about the CIG system architecture or the hardware modularity or the correctness of the image processing algorithms. He probably doesn't even know how much hardware is working together to produce the composite illusion he's immersed in. Almost all of his impressions about the system and its overall effectiveness will hinge on what he sees, both in and outside the cockpit, as he executes his mission. For the system to be effective, the visual environment model must be effective, and this requires careful optimization of the data base model. The CT5A system is complemented by a comprehensive modeling technology which helps wring the most visual mileage out of every part of the data base.

High Fidelity Components

If the training mission is to be accomplished successfully, certain key ingredients of the visual scene must succeed in conveying the subtle and realistic cues the pilot requires. This means that lead aircraft, formation aircraft, refueling tankers and enemy targets must all be modeled to provide maximum fidelity and recognizability. New methods of complex surface polygonization are used to produce models that better represent the actual hull shapes and shading while reducing polygon loads. New ideas and methods for the design of lead aircraft have produced models that can be used for formation flight, yet leave enough capacity for special effects and a rich terrain environment.

A new method for complex surface representation based on planar quadrilaterals has replaced the previous use of triangles. The use of four sided surfaces instead of triangles has significantly reduced IG load while improving the visual appearance and fidelity of the resultant models. In the past, use of triangles

tended to produce models that wasted polygons in areas of little curvature and caused shading problems because of small 'hills' and 'valleys' which inevitably occur at the junction of each pair of triangles. One quadrilateral can be used to replace two triangles, and will eliminate the small erroneous surface perturbations. An example of this method is shown in Figure 5, which illustrates the forward portion of a ship hull. The complex curvature was first solved with a mesh of triangles. A reworking with quadrilaterals reduced the polygon count by nearly 50%, while providing a surface structure that is more complex, has more detail, and presents a more accurate silhouette which is more representative of the actual ship. The methodology underlying this strategy includes a sectioning process which anticipates and supports the use of four sided surfaces to do the eventual skinning.

One of the most important items to accurately represent in a data base is the lead or formation aircraft. The problems in modeling a lead aircraft include providing visual cues across the wide range of distances required for formation flight within the limited resources of the CIG. Current solutions to these problems include the creative use of fixed shading, smooth shading, color blending and transparency. Several levels of detail are used to include structures that would otherwise be excluded due to excessive IG load. The F-15 in Figure 2 is based on a bare aircraft hull model of less than 300 total polygons, and is a good example of these strategies at work. As the photo illustrates, a visually complex terrain model can also be displayed which includes many small details. This capability is also illustrated in Figure 1, where an F-15 is seen chasing a MIG over a culturally rich, navigationally specific terrain area.

Terrain

For the new generation of tactical fighter trainers much more is demanded of the terrain imagery than merely telling the pilot which side of the sky is made of rocks. To be fully effective in training for the strike mission the data base terrain must be navigationally specific, and dense enough to provide realistic levels of terrain masking for embedded enemy counter measures. It must provide the high levels of optical flow the pilot requires to fly his craft at treetop height, and must cover geographic areas large enough to provide a meaningful mission context to the training exercise.

These requirements, taken as a whole, imply staggering amounts of model data. The density of visual cues required to support these flight objectives can be calculated easily[(4)], and the total data base content is simply the product of the required density times the overall size. The end result is a requirement for massive amounts of data base development funding, and some very real questions about whether the image generator can handle such a data base[(5)]. We have addressed these issues by developing a new and significantly different approach to visual data base development. This approach centers around the notion of building navigationally specific terrain out of reusable terrain patches which are further embellished with reusable organic and cultural features.

The Basis Set Approach

In this strategy, scene features are typically modeled only once. Off-line processes are used to create variations of each feature, such as orientation, size and coloration. The resultant library of features is then made available to the modelers for inclusion into the data base at appropriate locations as required to make each terrain region correspond to a particular section of the earth. The actual addition of these features to the terrain is done interactively using a real

time graphics work station. What is actually submitted to the IG hardware for each feature is a pointer to the library version required, plus a three component positioning vector. The IG will use this offset vector to position the item, and will reference the single copy which is required from its internal memories. This instancing function is very general, and can be applied to arbitrarily large portions of the data base. When the offsetting occurs, any accompanying visual priority data and LOD features automatically move with the item, preserving the correct visual appearance and behavior.

This process greatly reduces the amount of modeling which must be done, and the quantity of data which must be on-hand at any instant for the image generator. This notion has been applied to the problem of lineal features such as communication lines, roads, rivers, and coastline with appreciable effectiveness. A very powerful general extension is now being used to create the terrain skin itself by instancing a basis set of three dimensional terrain patches. This allows the creation of specific, detailed, map correlatable terrain with a rich, dense embellishment of two and three dimensional textural features, such as shown in Figures 3 and 4. These data bases are modeled from elevation grid data and represent large areas of Fort Hunter-Liggett in central California. The density of visual cues is designed to support nap of earth flight, and exceeds 500,000 surfaces per square nautical mile. The major difference between these two data bases is the content of the terrain basis sets, and additional major variations in vegetation type could be created with minimal effort.

TODAY, TOMORROW, AND THE FUTURE

Today, the CT5A visual system is in production for the Marine Corps AV8B Advanced Harrier operational flight, weapons and tactics trainers. The data bases for these systems include map correlatable flat and mountainous terrain for regions of the east coast and west coast totaling more than 100,000 square nautical miles. This system includes all of the special effects which have previously been mentioned. The simulator environment includes a large dome with a multi-channel FOV covering more than one hemisphere.

During the last few months the Air Force has been testing a CT5A limited FOV visual system for addition to the F-15 flight simulators. This system is designed to present up to five friendly or threat aircraft while also presenting dense, navigationally specific terrain. The aircraft include two types of friendly and two types of threat aircraft that have selectable speed brakes and afterburners. The formation aircraft also have cycleable landing gear. Also included are air-to-air missle launches, surface-to-air missles, anti-aircraft artillery, and bomb impact. The two photos of the F-15 were taken over the data base that is being used for this test.

In the near future the CT5A system will have many improvements, including the addition of hardware texture and non-linear (spherical) image mapping. These new features will increase the visual effectiveness of the system substantially and allow it to better address the need for very wide FOV applications. Such a system can provide those first fifteen very realistic tactical engagements that will help each pilot survive. Such systems can give the experienced pilot the continued training that will keep his reflexes and knowledge sharp without the cost and risks of actual flight or actual combat.

Figure 1 - F-15 in Tactical Area

Figure 2 - F-15 Near Airport

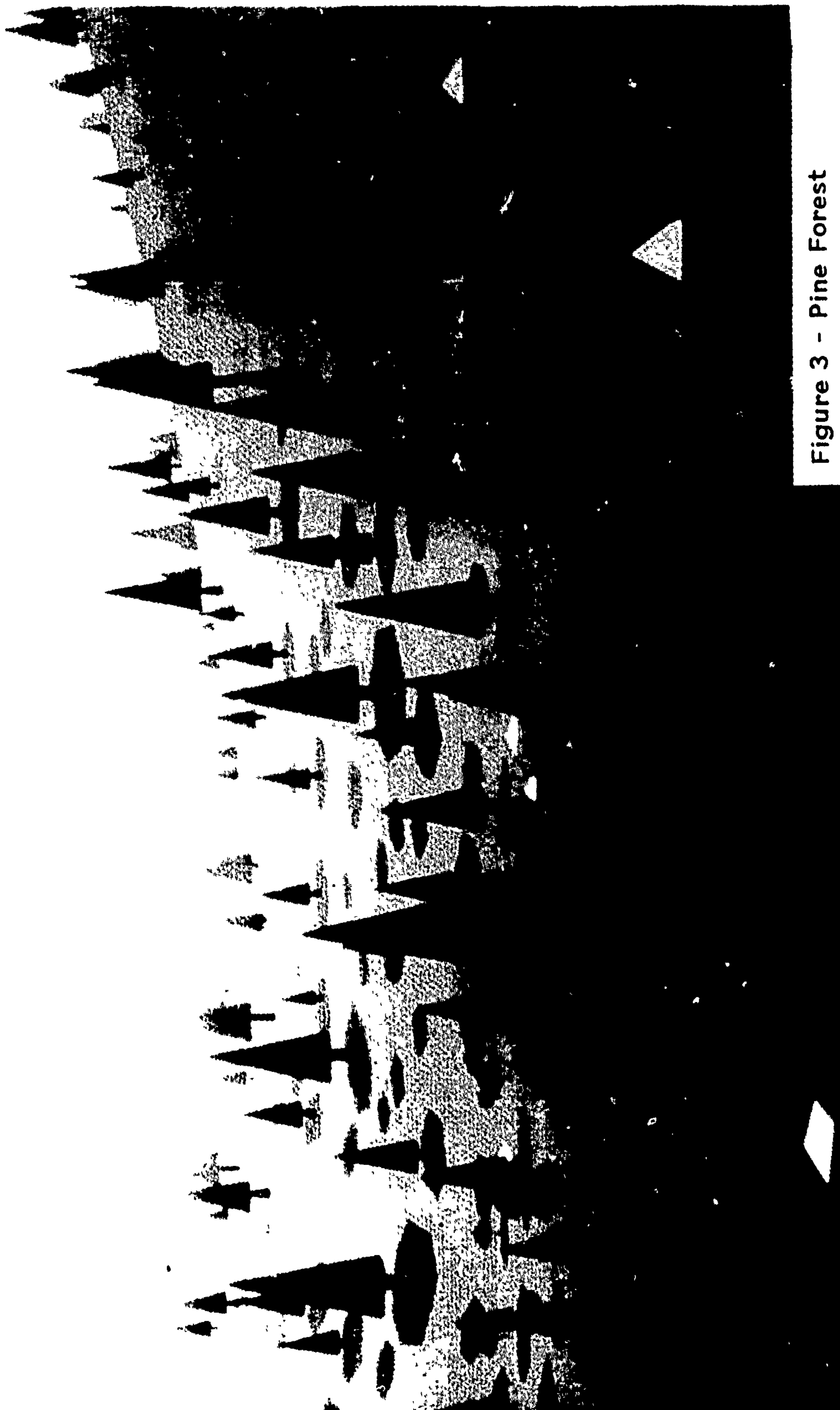

Figure 3 - Pine Forest

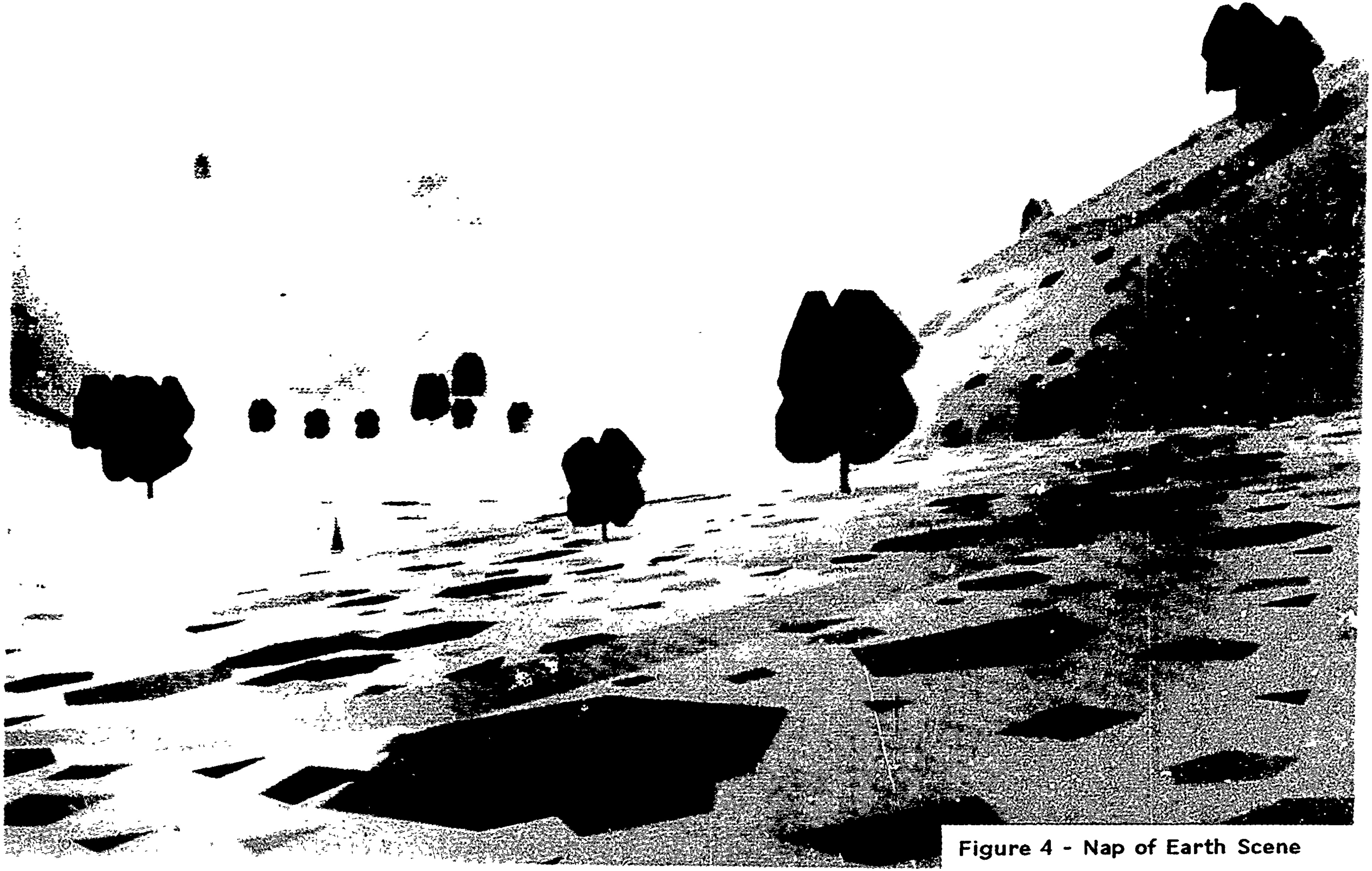

Figure 4 - Nap of Earth Scene

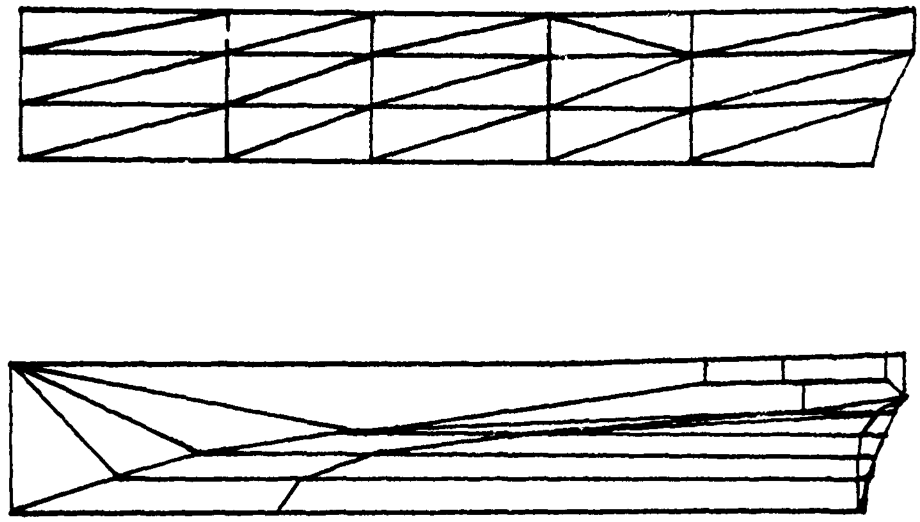

Figure 5 - Ship Hulls

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Military Applications of the Singer Link-Miles IMAGE Visual System

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Abstract

The objectives of this paper are to demonstrate how the analysis of training requirements and the selection of appropriate new technologies have enabled Singer Link-Miles to provide task-oriented military visual systems. The IMAGE system evolved from low-cost light-point-only systems applicable to early commercial airlines requirements. The latest full daylight system employs raster/calligraphic techniques with a full colour capability. This system has been augmented to meet military training needs. Prior to the adaptation of current technologies, extensive analyses of customer training requirements were carried out. Hence the information content of the visual has arisen from a thorough understanding of the tasks being performed by the crew. In discussing the analysis of training tasks, several human factors techniques are available. A realistic approach, however, has been taken in view of the time/cost restraints inherent in a commercial organisation. Emphasis has been placed on 4 major areas: Strategic Analysis; reference to Training Curricula; Flight Experience and Future Strategies. These varying military requirements have been met by exploitation of the latest microprocessor technology. This technology has allowed flexibility and expansibility only where it is needed. The corollary of this approach is that training is supported by TASK-ORIENTED VISUALS.

CONTENTS

1.0 Introduction

1.1 The Evolution of IMAGE

At the present time, computer generated flight simulator visual attachments that provide "out of the window" visual scenes can be placed in one of two classes. The first gives maximum performance, in terms of the amount of scene content and extent of gaming area, and employs a full colour, raster scan display. The second class has evolved from low-cost, light point only systems which were developed initially to meet the commercial airline training needs and employ calligraphic (vector writing) deflection, at least for light points. These latter systems have increased in capability over recent years by the addition of surfaces to provide dusk and, more recently, day scenes. IMAGE II and IMAGE III are the names assigned by Singer-Link to a new generation of CGI visuals belonging to the latter class. IMAGE II, uses a beam penetration CRT, providing a Dusk/Night scene meeting the Phase 2 requirements of the FAA simulator regulations AC 171-14 and IMAGE III is a full daylight system meeting the Phase 3 requirements of these FAA regulations.

1.2 The Potential of IMAGE

The question to be addressed by this paper is how the IMAGE system which, as a base-line system, is designed to satisfy the airline training requirements - with its emphasis on terminal buildings, taxying, take-off and landing - can be extended to meet many military requirements where actual airfield operations are of much lower priority. It will be shown that the inherent flexibility and expansibility of the system allows many such requirements to be met in a cost-effective way through the careful analysis of these requirements, to produce a task oriented training program.

1.3 IMAGE Applications

Since the launch of IMAGE in February 1982, 46% of visuals sold have been for Military applications.

The types of military flight simulators using IMAGE systems range from the large multi-engined aircraft to small ground attack aircraft. Helicopter applications include maritime ASW and helicopter anti-tank scenarios. The unique field of view requirements for VSTOL operations were met using a 3 channel, 3 window system. This provides the ability to operate from the ski-jump of an aircraft carrier.

2.0 Method

2.1 Current tendencies in Training Philosophy

Unlike the training needs of the commercial airline operators, military scenarios provide a formidable repertoire of widely varying tasks for aircrew. Military customers for flight simulation equipment are now very aware of the need to satisfy specific training requirements. Consequently, these customers are intent on selecting the appropriate technology to meet those training needs. The corollary of this argument is that training requirements must be defined first.

2.2 The need to define User Requirements

This paper is concerned principally with those features of training relevant to the visual display. In this part of the simulation process it is just as important to define the training value expected of the visual. Further, the information fed into the visual system arises from a thorough analysis of the tasks being carried out by the crew at any one moment during the mission. Only in this way can the visual system support the training function throughout that mission.

Military requirements can best be summarized by describing a list of important scenarios. Very early on, a portfolio of scenarios was identified into which most of the military training functions would fall. That portfolio is as follows:

2.2.1 Military Airfield

2.2.2 Low-level navigation

2.2.3 Air Combat

2.2.4 Ground Attack

2.2.5 Helicopter Operations

2.2.6 Maritime Reconnaissance

2.2.7 Flight Refuelling

2.2.8 Tank Driving

2.2.9 Weapon Effects

2.2.10 Special Effects

2.3 Mobilising the Resources of IMAGE to fulfil Training needs

So far, this paper has described two sequential processes instrumental in supporting methods of military training. That is, recognising customer tendencies towards training and recognising the need to define user training requirements.

The third process of this method is to mobilise available resources, in this case the IMAGE system, towards fulfilling training objectives. It is important to note that without the first two processes the necessary information is not available. Requirements must come first, then the content of the visual can support the tasks to be performed. The corollary is that TASK ORIENTED visuals are developed.

2.3.1 Task-Oriented Visuals

All computer generated images provide only an abbreviation of the real world. Scene detail is severely restricted. Common metrics of scene detail are numbers of edges or surfaces. At first sight, the capability of IMAGE to provide 250 surfaces may seem small. However, it is important to realise that this figure applies only to those surfaces actually visible to the observer at any one moment. The tot.. surface capability for a database approaches a much greater figure. More important still, is the fact that this scene capability applies to each channel of IMAGE. For example, a 3-channel IMAGE can display 750 database surfaces simultaneously. However, the actual number of observable surfaces can be significantly greater by the use of surface overlay techniques. Further, with the IMAGE system, a database surface polygon can have up to 15 sides enabling complex objects to be efficiently modelled with fewer surfaces.

The significant of defining user training requirements is to achieve optimum distribution of those available surfaces throughout the visual scene. That means, putting the information where it is needed and not displaying information which is irrelevant to the task undertaken by the crew. For example, in air-to-air refuelling, most of the important information resides on the underside of the tanker. For ground attack, targets and significant ground features take precedence in the allocation of surfaces to the scene.

In summary it can be seen that the tasks being performed by the crew dictate distribution of scene detail.

2.4 Techniques to Establish User Requirements

There are a variety of human factors techniques used to carry out task analysis. In some cases these methods extend to measurements of human performance and can be very tedious and time consuming. In a commercial environment many of these approaches, with respect, are impractical unless large resources of time, money and manpower are available. In fact, Singer Link-Miles make use of extensive literature provided by research personnel who do have the above resources. An effective approach is to take an overview to the training requirement at scenario level. Four techniques are mentioned briefly, here, which help to break the scenario down into a sequence of mission phases. These mission phases can be further broken down until the individual tasks of the crew are revealed and understood. The techniques involve:

* Strategic Analysis
* Analysis of training curricula
* Flight experience
* Knowledge of future strategies

2.4.1 Strategic Analysis

It is important to understand the overall strategy of the military scenario in question. That scenario can be considered in systems terms. A system is a bounded complex of elements, inter-related by processes which respond to events to achieve an objective. Therefore it is appropriate, first, to identify the individual system elements. For example, the friendly and hostile platforms whether land, sea or air. Having identified these elements the next process is to establish the communication links between those elements. It is likely, after this analysis, that a central communications centre will emerge.

The degree of autonomy enjoyed by the different elements will also be revealed and can have a bearing on the likely behaviour exhibited by any particular element. If possible, draw a picture of this scenario of inter-related dependencies on one sheet of paper so that the whole scenario is visible at a glance.

Fig. 1 illustrates such a scenario used to analyse the training requirements for helicopter anti-tank warfare, produced from the analysis below.

2.4.2 Analysis of Training Curricula

Almost without exclusion, military customers provide thorough, easily interpreted manuals which set high standards of user capability. These manuals usually take the form of Operating Procedures. From this data, information can be extracted which determines the tasks of each individual in the system, whether it be Flight Refuelling, Helicopter Anti-tank warfare, or any other scenario.

2.4.3 Flight Experience

Gathering data and talking to users provides invaluable information. However, there is no substitute for experiencing and getting involved in the actual task for real. Details emerge which are not easily put into words. Information becomes apparent which the user may not have considered important to convey. Procedures are revealed which may vary slightly from the procedures manual or which may have arisen from recent changes in operational methods.

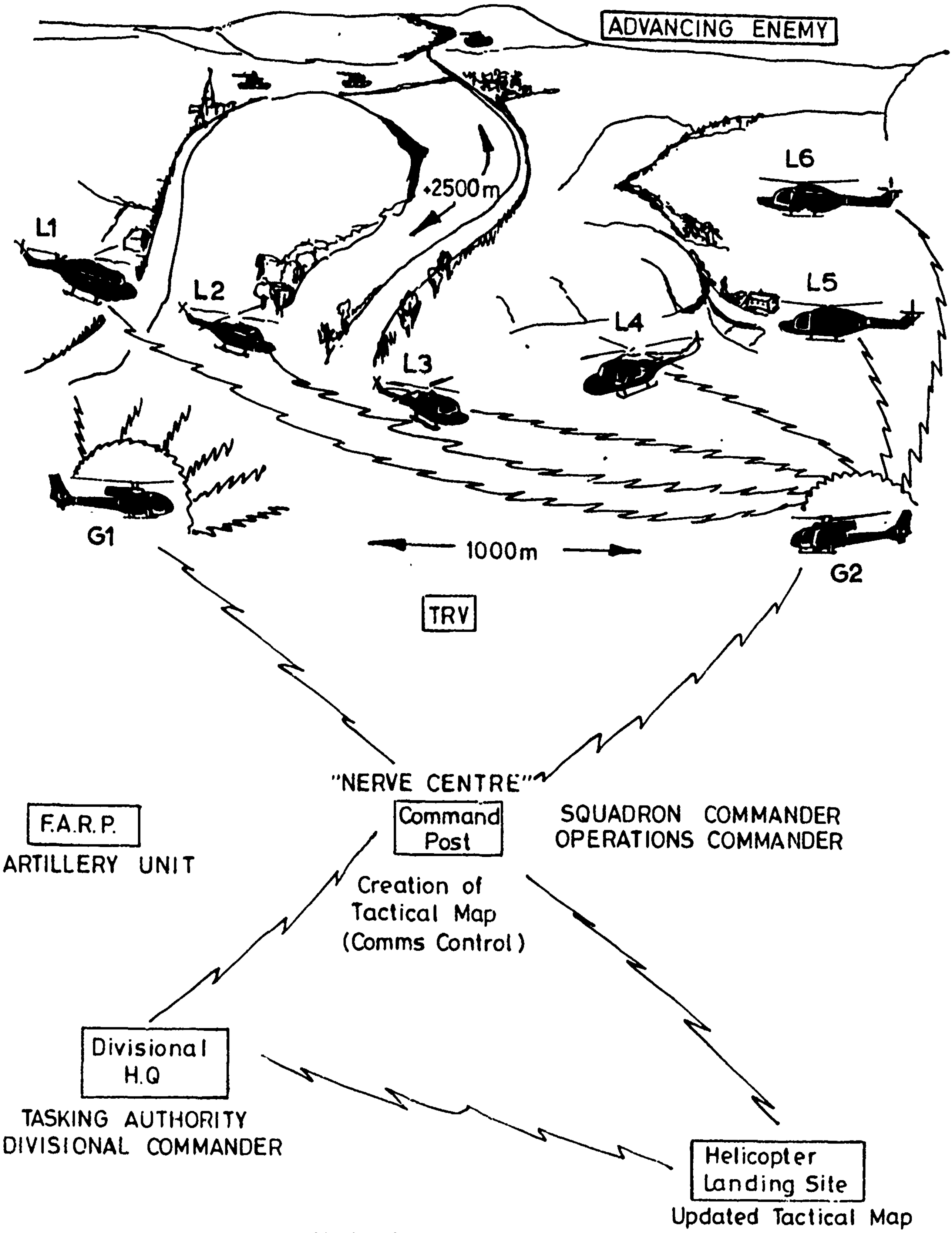


Fig.1 ANTI-TANK BATTLE SCENARIO
(UNDERSTANDING THE STRATEGIC SCENARIO)

Singer Link-Miles go to great lengths to arrange flight experience where availability and restrictions permit. Investment in sophisticated video equipment suitable for varying visual conditions has been made. By this means it is possible to record visual impressions and operational procedures and, further, analyse them in a laboratory environment.

2.4.4 Knowledge of Future Strategies

Over a period of time operational requirements can change. During that period, new training techniques and equipment emerge. If it is at all possible, flexibility must be designed into the visual system to accommodate these changes. For example, target designation by laser sighting systems during low and high speed ground attack. Equally important is the need to be aware of future techniques in simulation which, for example, provide considerable improvements in fields of view and resolution.

2.4.5 Summary of Techniques to Establish User Requirements

Using the above techniques, useful information emerges. For example, taking the chosen scenario, it would be possible to:

(a) Identify key personnel and define their responsibilities.

(b) Understand the hierarchy of personnel and equipment, both for air and ground support.

(c) Focus attention on the helicopter and the phases of the mission within which it is involved.

(d) Scrutinize the helicopter crew tasks and define the skills required to carry out those tasks.

By understanding the whole scenario the tasks carried out by individual members of the team become more meaningful. Table 1 is a summary of some of the important tasks and skills. This analysis, incidentally, revealed that the helicopter crew members exhibit markedly different behaviour at the same point in time. This can have an important bearing on the information supplied to each member through the visual system.

TASKS	SKILLS
* Route Planning and Navigation	Map reading; contingency planning; operation of navigation system
* Communications	Radio interpretation
* Change of Plan/ Strategy/Re-locate or withdraw	Mental agility and flexibility Decision making
* Visual contact with Enemy	Target/pattern recognition
* NOE Flying/Stand-off Range Hover	Judgment of Height, Speed, Distance and Proximity, Operation of flight system
* Check/Operate T.O.W. System	Working knowledge of system
* Locate Ideal Position and avoid Detection	Field Craft - Experience
* Concentration over time under stress	High mental and physical resolve

Table 1 : Crew Tasks and Skills: Pilot/Gunner

(Not Exhaustive)

3.0 Enhancements to IMAGE

From the start of the development of IMAGE it was recognised that the system would need to meet the varying requirements of both the Phase 2 and Phase 3 FAA regulations for commercial airlines as well as the extended requirements for military users. At the same time the incorporation of features required for the latter but not necessary for the FAA approved system should not significantly impact the costs of the base line system. With these factors in mind, the system architecture and detailed design was implemented with a view to meeting these varying requirements with minimum changes and with easy upgrading capability. Thus the base line dusk/night IMAGE II can be field upgraded to a full daylight IMAGE III by the replacement of the displays and the addition of a few cards to the existing cardbins, and further upgraded with the texture sub-system by the addition of a further cardbin in the existing racks. Additional special Military requirements, such as additional targets and feedback of ground height data, can be met by expanding the processing power by the addition of a small number of circuit cards.

This flexibility and expansibility has largely been achieved through the exploitation of the latest microprocessor technology. A block diagram of the IMAGE system is shown in Fig 2 . The first point to note is that there is no dedicated visual minicomputer; the function of this has been absorbed by the microprocessor based Database Processor Unit (DPU). The development of IMAGE coincided with the availability of the new generation of powerful microprocessors which made it feasible for the first time to perform these functions cost effectively in such a manner. Typically 4-5 microprocessor boards are used in the DPU; these boards were designed by Link based on the INTEL 8086/8087 processor chips. The active database is down-loaded from the Peripheral Communications Unit (PCU) which contains a Winchester disk holding all available databases. The DPU performs all software tasks associated with selecting in-view database segments, object priorities, host interface

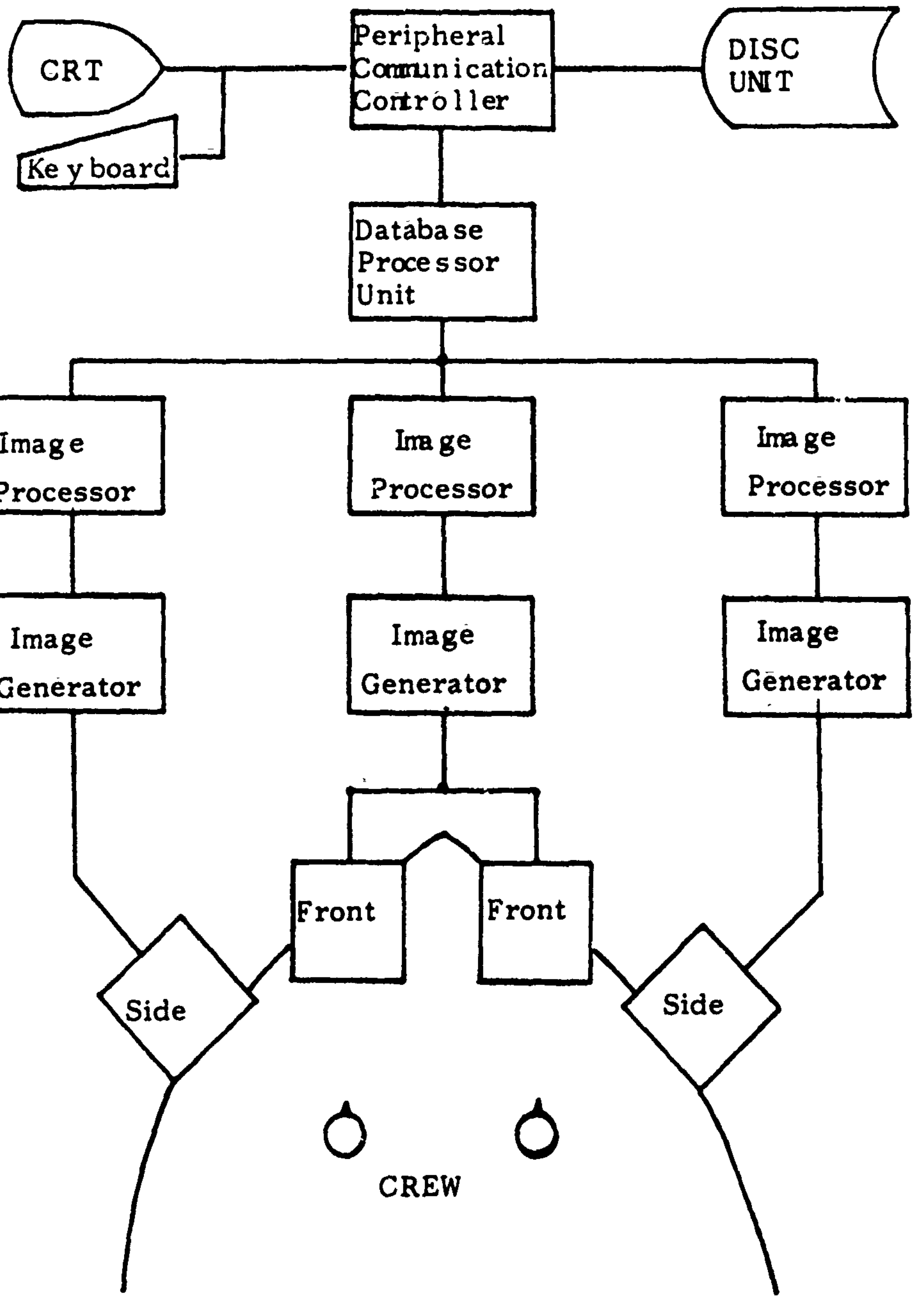


Fig 2 : Block Diagram of 3 Channel IMAGE system

controls, matrix coefficient calculations for the Image Processor Unit (IPU), target movement and position, and built-in-test routines. The functions of the DPU include most of the application dependent functions. With Military applications, the requirements for more moving co-ordinated systems (e.g. targets), larger databases, requirement for feedback from the visual system on terrain height profiles, computation of terrain for the texture system, weapon release effects, rotor flicker, etc. can result in the computing capacity of the base line DPU to be exceeded. The advantage with the IMAGE DPU system is that the power of the DPU can be expanded in low cost increments by the addition of another processor circuit card and associated memory, whereas with the previous approach, using a separate computer, the expansion to an additional computer, or a more powerful version of the series, resulted in a major cost jump, plus possibly a major software rewrite. Examples of this increase in the number of processors are the addition of a fifth processor card for IMAGE III to reduce the frame time from a nominal 33 msec to 20 msec to give a flicker-free daylight display, and the addition of a processor card dedicated to feeding back terrain height in function in a recent helicopter simulator.

The IPU performs the standard perspective transformations between database and eyepoint co-ordinates on surface vertices and light points. This also uses microprocessors, but these are built out of fast bipolar bit-slice processors. This allows many functions to be carried out with common hardware with the specific function determined by the built-in firmware. Generally speaking the function of the IPU is not application dependent although the pipelined structure would allow an additional bit slice processor to be added to meet a particular new requirement. Modifications have been made to the IPU to meet the more demanding requirements of military flying but since they have affected firmware, rather than increasing the amount of hardware, these have been incorporated in the base line system. Fig. 3 shows the expansibility of the processors: horizontal expansion in the DPU through additional parallel processors and vertical expansion in the IPU by means of adding processors to the pipeline.

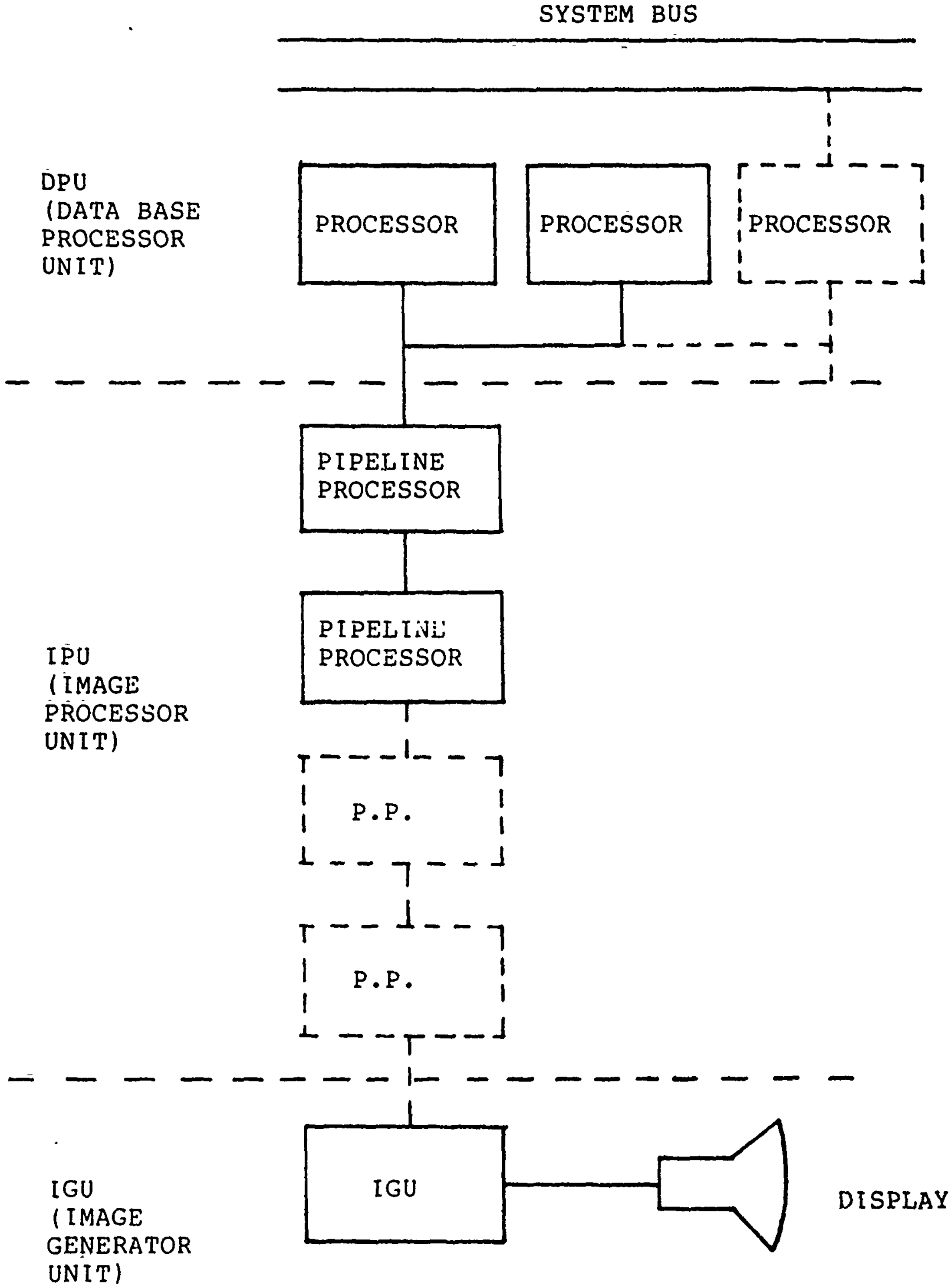


Fig 3 : Processor Expansibility: horizontal in the DPU and vertical in the IPU

The IMAGE system uses the calligraphic mode to display light points without scintillation, with good brightness and high positional resolution. Surfaces, however, are displayed in a single high resolution (1000 line) vertical raster. The Image Generator Unit (IGU) takes the surface and light point data from the IPU and processes these to provide the appropriate signals to drive the display device. The IGU also adds special effects such as low visibility and landing lights. The addition of non-edge based texture patterns to the ground plane, sea, or clouds, is an option particularly useful for certain military applications because of the assistance given to assessing height and translational velocity . This is an extension to the IGU as shown in Fig. 4 and is contained in an additional cardbin based in the same rack as the IGU.

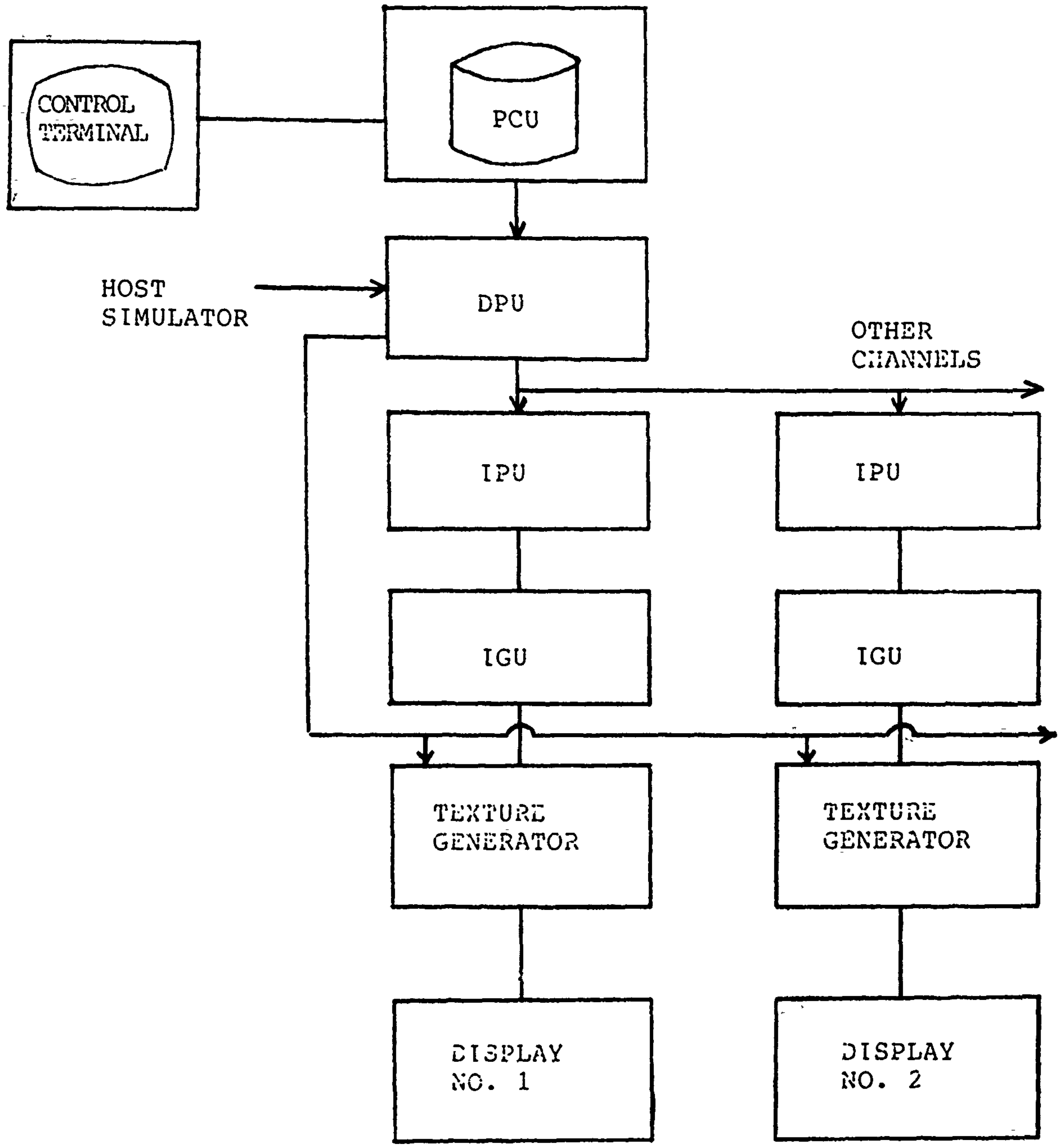
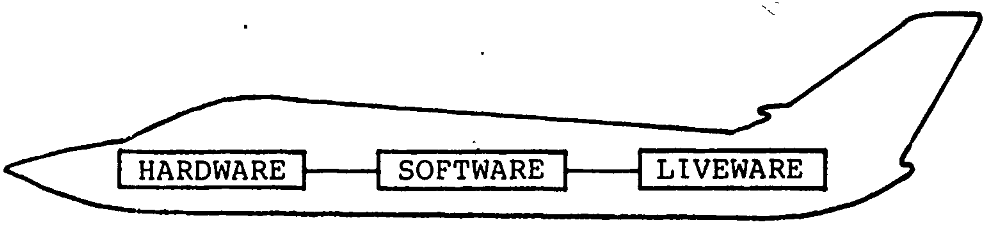


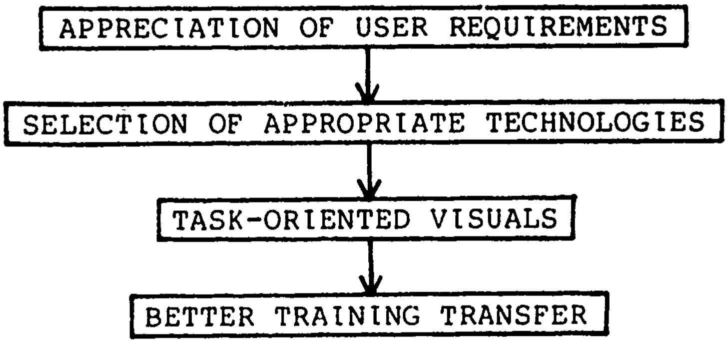
Fig 4 : Extension to the IGU for Texture Patterns

4.0 Conclusions

This report has discussed the evolution of the IMAGE system both from technological and Human Factors standpoints. The results of this approach have been to attempt optimum matching of available technologies to meet training requirements. In systems terms it is appropriate to consider the user as the LIVEWARE. Hence the ideal system is an appropriate blend of hardware, software and liveware.



Inevitably, such a system will be a compromise of these ingredients. However, the end result will be greater user satisfaction due to the benefits of increased training transfer.



AVTS: A HIGH FIDELITY VISUAL SIMULATOR

Robert L. Ferguson received his M.S. in Systems Engineering from the University of Florida in 1972, and his B.S. from Rensselaer Polytechnic Institute in 1968. His 15 years of experience at General Electric have included hardware and software design, systems analysis and design, and project engineering on a variety of image processing and visual simulation projects. His ten years in image processing centered on the development of interactive satellite image processing and information extraction systems. The last four years he has served as the Lead Systems Engineer for the Advanced Visual Technology System, a high performance TACAIR mission visual simulator.

AVTS: A HIGH FIDELITY VISUAL SIMULATOR

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ABSTRACT

The Advanced Visual Technology System (AVTS) was developed under the auspices of the Air Force Human Resources Laboratory (AFHRL) to satisfy the demanding TACAIR mission visual system requirements. In particular, the requirement for low level flight through a high density, wide FOV, rolling terrain environment with a large number of moving models on and above the terrain surface posed a formidable system design problem. New developments were required in the critical areas of VDB structure, feature selection, priority, load management and blending to achieve the requisite scene content. This paper will discuss the advancements made in these areas, and show that an integrated system design process was essential to the success of the project.

INTRODUCTION

The Advanced Visual Technology System (AVTS) is a Computer Image Generator designed to support training research for the latest generation of USAF fighter aircraft. Though developed under the auspices of the Air Force Human Resources Laboratory (AFHRL), the AVTS is to a large extent the evolutionary product of many years of CIG research and development at General Electric. The AVTS is designed to satisfy TACAIR mission requirements, including low level flight, air to ground and air to air combat, aerial refueling, and conventional airfield operations for high performance fixed wing aircraft. Recently, the program has been expanded to incorporate the requirements of the Visual System Component Development Program (VSCDP), which addresses the simulator problems associated with Army combat helicopter training research. This combined mission synergy places the AVTS at the forefront of visual simulation technology.

The AVTS was originally specified as a 10 channel CIG, capable of generating 4000 faces, 4000 point features, and 1000 circular features, with conventional texture, curvature, and fading modulations, operable at 30 and 60 Hz update rates and capable of supporting a high density, rolling terrain environment with a large number of moving and fixed features throughout the gaming area. The VSCDP further augments these capabilities with cell texture, a modulation technique which produces photographic quality scenes, and an area-of-interest dome display system slaved to the pilot's line of sight.

The TACAIR mission requirements levied on the AVTS have necessitated major CIG advancements in three fundamental areas: image quality, display technology, and scene content.

Image Quality

Significant improvements in image quality have been made possible with the now cost effective full frame video buffer technology, which permits the CIG to be driven by "faces per frame" rather than by "edges per raster line" constraints. As a result, the compromises made in prior line oriented systems have been eliminated, resulting in superior quality imagery and at significantly lower cost. The new architecture has also made cost effective interlace smoothing to improve dynamic image quality, and translucency to eliminate "popping" as features are activated or transition between levels of detail.

Last but not least, VSCDP enhances image quality even further by introducing a new IR&D development called cell texture, a face plane modulation technique which results in photographic quality scenes. Each face in the environment can be designated to be covered with either a cell texture pattern or conventional stripe texture, and both forms of texture maintain the perspective accuracy and image quality of the underlying face, regardless of orientation.

Display Technology

AVTS was originally specified to drive the existing wide field of view ASPT dodecahedron, retrofitted with high resolution color light valve projectors. VSCDP will improve on this concept by developing a high brightness color light valve dome projection system with an area-of-interest projector slaved to the pilot's line of sight. For details the reader is referred to Ferd Neves's Image III paper, "Design Considerations for an Eye Tracked AOI Display System".

Scene Content

Clearly, a "rich" visual environment is essential to meet the low level flight and air to ground combat mission requirements. As a result, a dedicated pipeline architecture was utilized to achieve the required feature capacities; edge conserving circular features were introduced; 3-D texture or ground clutter features were incorporated throughout the gaming area; improved load management and blending techniques were developed to maintain the scene content closer to rated capacities; a priority scheme was developed to cope with low level flight through rolling terrain with large numbers of fixed and moving models; and a Visual Data Base (VDB) structure was developed in concert with efficient multi stage feature culling techniques to ensure an adequate data flow from the VDB disk through the CIG, even at maximum ownship velocities.

This paper will examine in detail some of the scene content related CIG design issues just enumerated.

THE PROBLEM

The requirement to develop a CIG with a "rich" visual environment for high performance aircraft posed many problems to the AVTS design team. From the outset it was recognized that it was a multi faceted problem, affecting all areas of the system, from the off-line software and VDB structure to the real-time software and hardware. As a result, the solutions evolved in iterative fashion, with each proposed approach beat against the various subsystems until workable solutions finally emerged.

It was recognized early on that a dedicated pipeline architecture would be required if we were to meet the face, point, and circular feature capacity requirements at a 60 Hz update rate. Furthermore, it was necessary to develop efficient feature selection hardware equipped with the appropriate hooks and handles to permit the load to be properly managed by the real time software. New feature activation and blending techniques were needed, all under software control, if full advantage was to be taken of the planned AVTS capabilities.

An early estimate of VDB block sizes and densities encouraged us to pay special attention to the block management problem: i.e., the paging of data blocks from the VDB disk and their transfer to the local memory. A dedicated computer interface path and double buffering scheme were specified as a result. Another fallout of the preliminary VDB analysis was the recognition of the need to increase 3-D feature density. Interviews with USAF fighter pilots reinforced the simulation literature with regard to the value of small ground features such as trees and cacti as low level flight cues. As a result, 3-D texture was introduced into the AVTS.

The feature priority problem was recognized at the outset to pose a formidable challenge. Previous techniques would simply not be adequate to meet the TACAIR mission requirements; ground and air moving models traveling on and over a rolling terrain environment posed severe occulting problems. A new approach was needed.

Finally, it was recognized that researchers required better quantitative measures of pilot performance to properly evaluate training effectiveness; i.e., the TACAIR missions necessitated that the AVTS be able to detect ownship collision and projectile impact with the many static and dynamic features of the visual environment.

The AVTS "front-end" soon took shape; see figure 1. Functions were allocated between hardware and software as shown in the diagram.

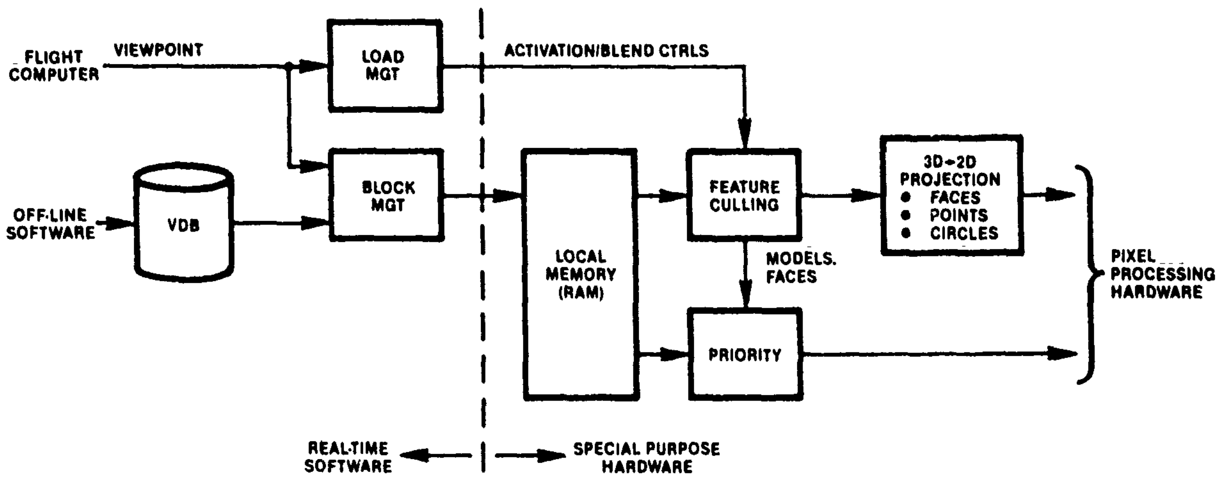

Figure 1. AVTS CIG Front-end

FEATURE CULLING

Feature culling is that process whereby a potentially visible subset of features is extracted from the local on-line data base; the subset selection criteria includes distance from the viewpoint to the feature, visibility within one or more display windows, projected feature size, and whether or not the front of the face is visible. There were two major problems to overcome: one was the sheer volume of data which the high density data base would develop, and the other was the large number of dynamic features to be generated by AVTS -- i.e., fighter aircraft, refueling tankers, tanks, trucks, projectiles, weapon effects such as flak puffs and fireballs, articulated parts such as flaps and landing gear, and others. Up to 128 dynamic features, each a unique set, were required per update cycle.

To solve the latter problem, a two stage rotation pipeline was developed. As diagrammed in figure 2, all dynamic features are rotated into environment space (normally, a geocentric spherical Earth coordinate system is used), the culling is performed on both static and dynamic features, and then a final rotation into one or more display windows is carried out. The traditional single rotation process, whereby features are rotated directly into window space and then culled, would have required an excessive amount of real time software computation.

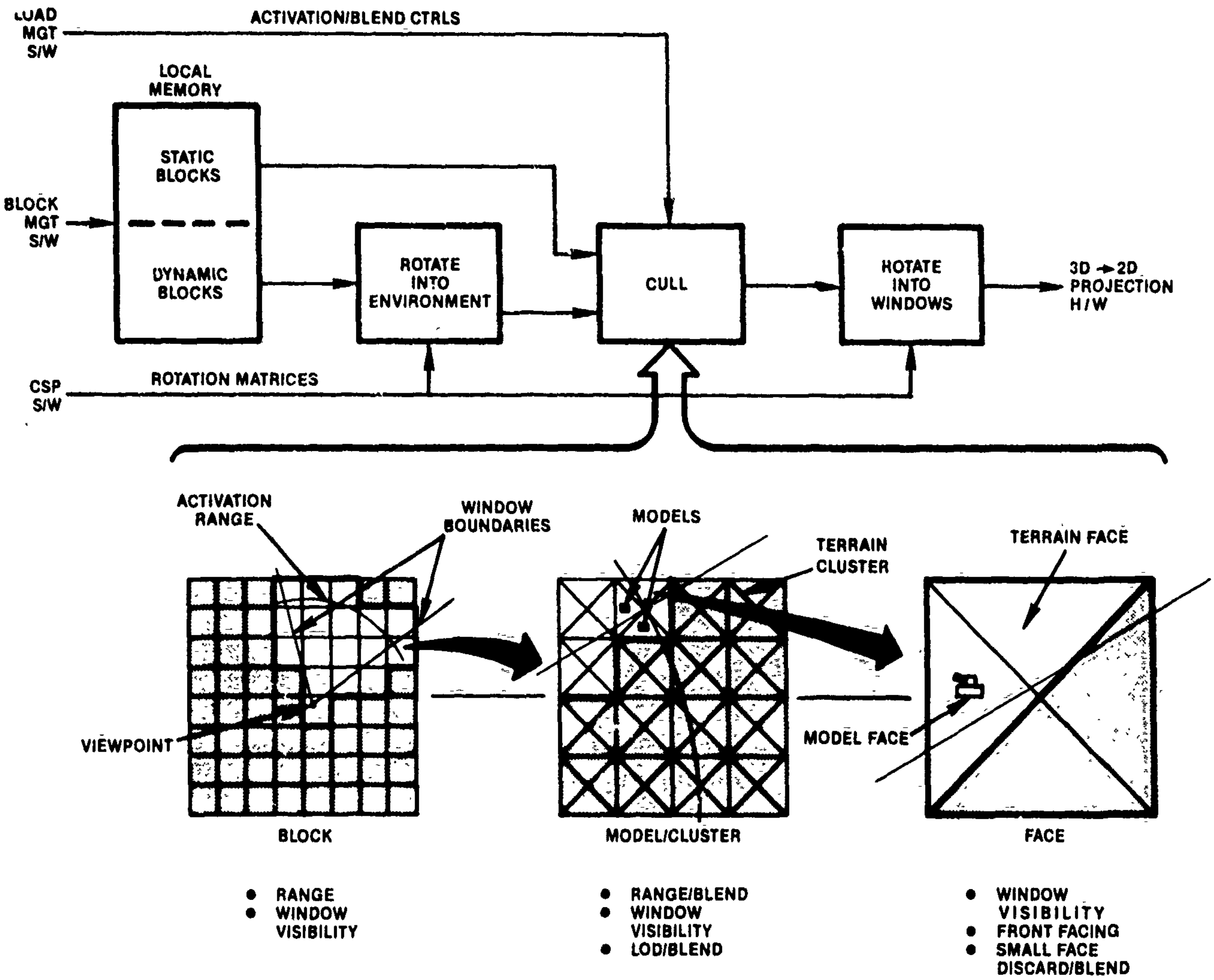

Figure 2. Feature Culling

The large data volume problem was solved by combining dedicated pipelined hardware with a hierarchical multi stage culling process. Preliminary data flow analyses resulted in the requisite clock rates for the critical path functions, and a specification for the local memory as a high speed multi port random access device. A dedicated pipeline architecture was clearly indicated. A three-stage cull was also indicated: blocks, models/clusters, and faces, as shown in figure 2.

Block Processing

All VDB data is grouped into either static or dynamic blocks, where a block is simply a fixed volume of data. Static blocks contain all fixed environment data-terrain, culture features coplanar with terrain, and fixed 3-D models-representing ground features contained within physical, rectangular regions of the Earth's surface. Dynamic blocks contain features which are controlled in position and attitude by the real time software, such as moving models.

Blocks are loaded into the local memory by the Block Management Software, and represent (in the case of static blocks) a geographic area in the immediate vicinity of the viewpoint. Static blocks are updated in real time as the viewpoint moves; dynamic blocks are loaded once at mission initialization. Furthermore, blocks may be declared valid or invalid by the real time software; invalid blocks, such as those on the opposite side of a thick haze layer, are ignored by the hardware cull, thus reducing the load on the hardware.

All valid blocks are tested by the hardware against software controlled range limits and active view window bounding planes. Blocks surviving both tests --i.e., within a prescribed range and visible in at least one display window--are passed on to the next stage of feature culling.

Model/Cluster Processing

A model may be a moving or fixed 3-D feature, such as a tank or a hangar. A cluster is a collection of up to four terrain faces and their overlying culture features (e.g. rivers, roads, fields). Models and clusters are range and window visibility tested, but only against those windows to which their parent blocks were assigned. In addition, level of detail (LOD) is computed as a function of projected size of the model or cluster. Model LOD is implemented by replacing the feature with a higher or lower detail version of the model; up to eight versions are allowed per model. Cluster LOD refers only to the 2-D culture on the terrain faces; the underlying terrain cluster is not allowed to change until it is sufficiently distant (nominally 8 nmi), at which point a coarser version of the terrain surface is substituted. Without this restriction in the terrain surface representation, high resolution area (HRA) insets, programmable field of view (PFOV), and LOD per window capabilities would be voided. The terrain surface would be discontinuous, and the models on it would appear to jump in the HRA and PFOV display windows.

Models/clusters surviving both the range and window visibility tests are passed on for face culling, at the computed LOD.

Face Processing

The final cull involves another display window visibility test combined with back facing and small face discard tests. "Small faces" are faces which project into only a few display pixels because they are viewed nearly edge on and/or because of their distance from the viewpoint.

Programmable Field of View

Another culling mechanism threaded through this entire process is Programmable Field of View, or PFOV. When activated, the PFOV concentrates the scene content within a set of user specified bounding planes by discarding all features outside them, unless specially tagged as peripheral features. The user is able to vary the PFOV in size from 1° x 1° to 179° x 179° in angular width and height. Furthermore, the PFOV pointing angle can be slaved to the pilot's line of sight or forced to track a moving target. This feature will permit experimenters to study the relationship between FOV and training effectiveness, and can also be used to help evaluate the utility of high resolution area inset displays.

The end result is a powerful front end able to sort through a VDB of unprecedented density at high speed. A worst case loading analysis demonstrated that an excess of 500 blocks, 2000 models/clusters, and 8000 faces could be processed in less than six milliseconds, resulting in a potentially visible set of 4000 faces passed on to the projection hardware.

3-D TEXTURE

It became evident during the design process that storage limitations would preclude the development of globally dense data bases unless some data compression of real world features was achieved. Terrain faces derived from DMA source data would provide an adequate representation of the Earth's surface, but there was no way to model 3-D features at sufficient density--i.e., hundreds of feet apart--throughout the data base without incurring prohibitive storage and modeling costs.

The concept of 3-D texture or ground clutter was therefore introduced. The idea was to sprinkle small, simple 3-D features such as trees, rocks, and shrubs throughout the data base via semi-automatic means. These features have been dubbed Environmental Universal Features, or EUF's. A location vector and type code is stored for up to 16 of these EUF's per terrain face which is in turn used by the hardware to fetch the selected EUF from a library of features permanently stored in local memory.

Since terrain face size is variable, EUF density is variable. The nominal AVTS terrain face density is 8.5 faces per nmi^2, which translates to 34 EUF's per km^2. The VSCDP VDB will increase terrain and EUF nearly five-fold, to 160 EUF's per km^2. Higher densities can be achieved by reducing the average size of the terrain faces even further.

The Storage Problem

Both off-line and on-line storage constraints required that each EUF "call" be kept to an absolute minimum number of bytes. Therefore, an apriori face priority scheme was developed; that is, the faces comprising the EUF are sorted based on a unique priority number provided by the modeler, as opposed to the traditional separation plane approach. Surprisingly complex features are able to be modeled, since object convexity is not required. Similarly, EUF's were constrained to be activated only within close range of the viewpoint, and could therefore utilize a common environment rotation matrix.

Local memory storage requirements for each call were reduced to 18 bytes as a result of the above techniques. Since EUF's averaged approximately 14 faces, each feature cost slightly more than one byte per face. This is in contrast to conventional features, which typically consume 100-150 bytes of storage per face. It is interesting to note that even with this 100:1 leverage, EUF calls have a significant impact on local memory; for the case of the AVTS delivered VDB, EUF calls constitute roughly one fourth of the static blocks. The alternative--specific features costing 100 bytes per face--would have increased memory requirements twenty-five fold, clearly an unacceptable burden. The local memory was ultimately sized at 512 blocks, which corresponds to an effective on-line capacity of approximately 800k faces, assuming 16 EUF's per terrain face.

EUF Culling

It was quickly realized that special methods were required to select only the potentially visible EUF's from the 50,000 or more stored in local memory. Once again the VDB structure provided the clue to the solution. EUF's were organized with their underlying terrain clusters, where each cluster was defined by up to four terrain faces. During model/cluster processing all terrain clusters with at least one EUF, visible in at least one window, and within the EUF range limit are saved in a separate list. Then an additional EUF culling stage was incorporated into the pipeline during which only those EUF's associated with these culled terrain clusters are range tested, resulting in a manageable set of potentially visible EUF's.

Experiments at AFHRL have demonstrated the value of 3-D vertical objects with and without 2-D surface texture for low level flight cues. The fact that these features will be generic as opposed to real world specific features should not diminish their usefulness as low level flight cues, since EUF's are placed on terrain faces which faithfully simulate the actual topography of the gaming area.

Furthermore, EUF's may be placed at specific locations via off-line interactive means, where appropriate. In addition, terrain faces are maintained at a fixed density to a sufficient range (nominally 8 nmi) such that the terrain surface appears stable to the pilot during low level flight. Finally, the cultural features overlying the terrain faces--the roads, rivers, and other landscape features--are not generic, but are real specific ground features. We felt that we could not do otherwise without significantly undermining the TACAIR training potential of the AVTS.

LOAD MANAGEMENT

The load management function was given attention early in the system design to ensure that the AVTS would be able to be fully exploited. The problem was multi faceted: underload and overload conditions required detection; the corrective action(s) must not be too quick nor too sluggish; the corrective action(s) -whether they be feature activation/deletion or LOD change--must not be visually distracting; and the load management strategy must be sensitive to the particular mission in question.

Detection

Over 60 parameters are monitored by the hardware and read back by the real time software every update cycle. Only a small subset are actually used to control the load, however all are available for statistical reporting purposes. A circular buffer is used to store the last 60 frames (or fields) worth of data; it is dumped on command or upon detection of an out of tolerance parameter.

Response Time

Filters with user controllable time lag factors are built-in to prevent the system from responding to sudden parameter spikes. Furthermore, user controllable upper and lower bounds create dead bands within which the system ignores input parameter variation. Finally, the various system load factors--the coefficients which vary the on-line range and LOD controls--are capped by user set upper and lower bounds and increment/decrement within these bounds according to user selectable rates.

Corrective Actions

Several strategies may be employed singly or in combination to change the scene data load: activation ranges for terrain, EUF's, and coordinate sets may be varied; LOD for individual moving models and/or all other features may be varied as a function of load and window resolution; and the size (in pixels) at which small faces are discarded may be increased or decreased. Furthermore, by properly setting the load factor bounds, the user may weigh one feature type over another. For example, during low level flight EUF's would likely be allocated a larger than normal share of the system capacity, at the expense of coordinate sets. For an air to air combat scenario the reverse would be true.

It was considered essential to carry out these load changes without distracting visual effects. As a result, several new blending techniques were developed for AVTS, all under the modeler's control. For the first time, features can be blended to the color of the feature(s) directly behind them, as determined by the hardware on a pixel by pixel basis.

Furthermore, four different blend weighting factors--the coefficients that determine the percentage of the intrinsic feature color to be mixed with the blend color--are modeler selectable singly or in combination. They are range, face size, model size, and translucency weighting.

Range weighting is used by features activated as a function of range, such as EUF's. Typically, 10 percent of the activation range is used to gradually blend the features from the background color(s) to the intrinsic feature color(s). Face size weighting is normally applied to the blending of culture faces, since they often become fragmented when they are projected onto the terrain by the off-line software. During low level flight this technique eliminates a significant number of small faces from the simulation. Model size weighting is used by features with multiple LOD's such as moving models, so that face colors will change at a uniform rate as the model blends between LOD's. Finally, translucency weighting--in which a modeler specified fixed weighting factor is applied--is used for canopies, windows, smoke, and other special effects with partial transparency.

Instantaneous Overload Control

The above discussion has dealt with the load management problem from a predictive standpoint; i.e., anticipate the overload/underload and compensate before it becomes extreme. There is a second strategy which is provided to the user: namely, instantaneous overload control performed by the special purpose hardware.

If one stage of the IG runs out of time before completing a given image frame (or field), the next stage in the special purpose hardware responds immediately by repeating the last image frame (or field). In effect, the update rate is momentarily decreased during the overload condition, thus preventing picture degradation. Whereas the predictive load management mode is more comprehensive, since it is sensitive to both memory and time limitations, the instantaneous nonpredictive mode has the property that higher nominal loads can be allowed. Maximum flexibility is gained by providing both methods of load management for the AVTS.

THE PRIORITY PROBLEM

It was clear at the beginning of the system design that a new approach to the occulting problem would be required. The driver was the requirement for low level flight over a high density rolling terrain with moving ground and air models. The key technical problem was the proper sorting of the terrain faces; once they were sorted correctly, all the features on and over them could be managed with existing sort techniques. Prior systems used range to the terrain face centroid as the sorting rule, but this was judged to be inadequate for AVTS. As figure 3 shows, viewpoints existed for which the sort would yield wrong priority values (the dotted line is the perpendicular bisector of a line connecting the centroids of the two terrain faces).

The technique that was developed to solve this problem took advantage of the VDB terrain data structure. The off-line terrain triangulation process generates convex terrain clusters consisting of up to four triangular faces. Since all clusters are convex, a footprint based on cluster vertices can be determined for each viewpoint, and a list formed identifying all clusters in potential conflict. The conflicting clusters are then sorted in pair-wise fashion by utilizing information derived from the respective footprints. The terrain faces within each cluster are sorted via similar methods.

Once all the terrain faces were properly sorted, all the culture, point features and 3-D features on and above each terrain face could be sorted amongst themselves via conventional methods--separation planes, range, layer number or apriori assignments. Priority between models on or above different terrain faces was then a simple matter of the

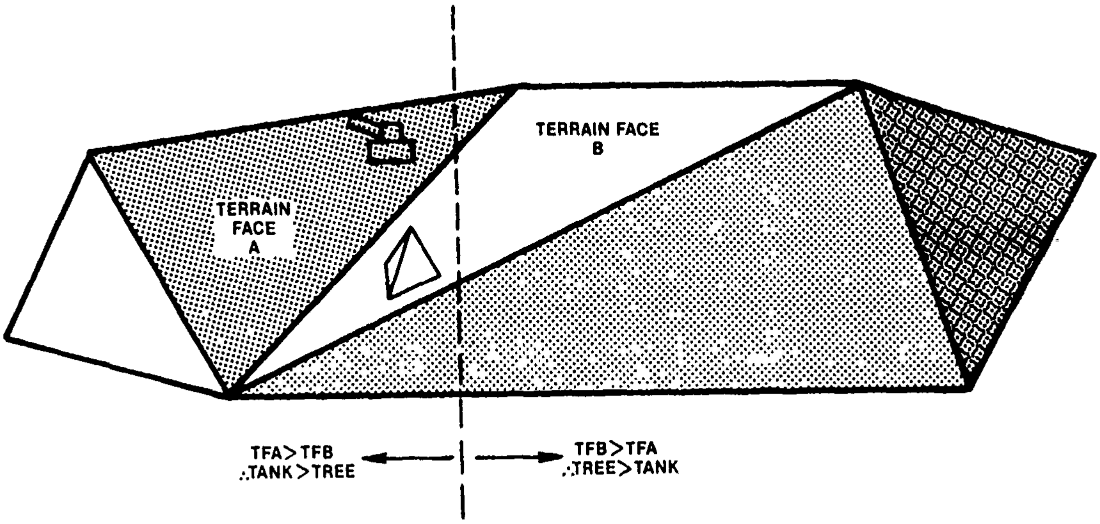

Figure 3. Incorrect Priority Due to Range Sort

relative priorities of the underlying terrain faces. This allowed models to be placed arbitrarily close to terrain face boundaries, a serious problem with range based sort algorithms.

Terrain faces are grouped into convex terrain clusters which in turn are grouped into convex, in fact rectangular, regions. The nominal region size for AVTS is 6 nmi by 6 nmi; however, the geographic coverage of each region is arbitrary. Thus, the VDB is structured as a regular grid of terrain regions, able to be expanded in areal coverage by simply adding more regions. More importantly, this grid structure permits the real-time software to be relegated the task of prioritizing the regions via a simple table look up.

A major benefit of this priority design is that models can move on and above the terrain with nearly complete freedom of movement. Clearly, models must stay separated by at least the sum of the respective model radii, but there is no need to constrain moving model paths to carefully constructed corridors. Model paths may even cross terrain face edges; these special boundary cases are handled by simply assigning the model to the highest priority terrain face (the model may be over as many as four at one time.)

Another benefit is that processing time increases approximately linearly with an increasing number of features, since the maximum number of features to be sorted in pair-wise fashion is bounded at relatively low values. Furthermore, density can be increased by simply decreasing region, cluster, and face sizes, without affecting the total processing time. For example, the VSCDP data base is approximately five times as dense as the AVTS data base--40 versus 8.5 terrain faces/nm^2 and 160 versus 34 EUF's/km^2. The only penalty is reduced range, a reasonable tradeoff.

PERFORMANCE MEASURES

A visual simulator must provide more than high fidelity and high density flight cues to successfully meet TACAIR training needs. In particular, quantitative measures of performance are required to properly assess training effectiveness. The AVTS has therefore incorporated a number of novel ownship collision and projectile impact measures in the system design.

The ownship - nominally an F-16 or A-10 - can collide with both fixed and dynamic features; in either case, a collision signal is generated, resulting in immediate visual feedback to the pilot. Collision between the ownship and his wingman is detected by the real time software; wingtip to wingtip, wingtip to fuselage, and fuselage to fuselage crash conditions are monitored. Collision between the ownship and the fixed environment is detected by the real time hardware; penetration of the terrain surface or 3-D models by extremities of the ownship is continuously monitored. The models to be tested are selected in advance by the modeler, thus permitting the system to ignore ownship penetration of smoke markers and clouds.

The pilot is able to fire his cannon, drop bombs, and fire air to air missiles, in various weather conditions and different times of day. To properly assess training effectiveness, the impact point of these projectiles must be determined. The special purpose hardware was necessarily allocated the task of calculating impact points with both fixed and dynamic features.

Impact with 3-D target models is computed by determining whether the projectile trajectory has intersected one or more invisible target spheres associated with each model. By defining spheres of appropriate location and radii for each target, the modeler is able to specify various zones of vulnerability. For example, a tank's back sphere might define a kill zone, in contrast to a tank's front sphere defining a damage zone. When impact is detected, a weapon effect (e.g., fireball) is placed in the simulation, followed by a damaged or killed version of the impacted target.

Impact of a projectile with the terrain surface is also computed by the hardware, and the exact impact point is returned to the real time software for scoring. Once again, a visual indication of impact is automatically inserted into the simulation to provide immediate visual feedback.

SUMMARY AND CONCLUSIONS

The AVTS does in fact support the scene content requirements for TACAIR mission visual simulation. A system solution to the multi faceted problems associated with wide FOV, high density, high fidelity imagery was found. Its success was shown to be the result of an integrated design effort, with all aspects of the system involved, from the off-line VDB generation software and VDB structure to the real time software and hardware.

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CONCLUDING REMARKS

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